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Methodology for the design assurance of aircraft lightning protection systems continued airworthiness.

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Abstract

This thesis describes a new approach to lightning protection components design by incorporating the use of multiple data sources, aircraft environmental threats models and component characteristics to determine if the component design meets the continued airworthiness requirements. This innovative aircraft lightning protection component design methodology examines critical component characteristics and evaluates these characteristics for long term survivability given known environmental design data. Use of in-service data, test data, material sciences and detailed component construction produces predictive results and provides inputs for the design community.

A simple case of non-active lightning protection components was used to validate this methodology, concluding that certain design degradation mitigations are necessary to improve the continued airworthiness performance.

Following this validation, the methodology was exercised by several case studies using actual design data from a large transport aircraft. The case studies provide for understanding how the methodology can be applied and showed that value was produced in creating design optimizations for the protection components. The case studies also proved that the methodology could be applied to different lightning protection designs spanning from structural design protection components to systems infrastructure transport elements and wiring. For this work, analysis sheets were designed to provide the necessary design assessments to apply the methodology.

Finally, the thesis concludes that application of this design methodology worked well for evaluation and optimization of lightning protection components and may work well for other aircraft system components. Future work associated with this study suggests that the methodology could more effectively deployed by use of an integrated computing system with the ability to share data efficiently between key design groups including electrical wiring design, electrical earthing engineering, electrical standards engineering, structural protection engineering and maintenance engineering departments.

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Chapter 1 Introduction and Objectives

1.1 General Description of Issues

Aircraft components that protect against the potentially adverse effects of lightning must be designed in compliance with identified aviation regulations. Aviation regulations must be interpreted in order to certify a new aircraft design for commercial applications. Methodologies for satisfaction of regulations rely on interpretation and negotiated mutual understandings of what is prudent and necessary to meet the intent of the regulations. The safety of flight is crucial to the ongoing success of commercial aircraft operations and a reliable worldwide transportation system. Both new and existing lightning protection technologies must be evaluated rigorously during a new aircraft development program.

Aircraft are typically designed to reach a particular Design Service Objective (DSO). This DSO refers to the flight cycle, flight hours, and calendar time goals used as a design parameter for the aircraft. The DSO assists engineers in the selection of materials and structural components. A typical goal for an aircraft economic life is 20 years but the flight cycle and flight hours will vary depending on whether the aircraft is designed for long distance or short distance applications. A wide body aircraft may be designed for a service objective of 20,000 flight cycles and 60,000 flight hours in 20 years. The aircraft DSO goals should be considered when selecting and evaluating lightning protection designs. This proposal leads one to also consider the continued airworthiness of lightning protection throughout the expected aircraft life.

The United States Federal Aviation Regulation, FAR 25.1529 states that, "the applicant must prepare Instructions for Continued Airworthiness in accordance with appendix H to this part that are *acceptable to the Administrator*." It is the interpretation of what may be acceptable to the administrator that drives a manufacturer to continue to investigate new ideas associated with how to determine and manage the continued airworthiness of aircraft structures and systems including lightning protection. As advancements in aircraft designs bring opportunity to evaluate new technologies and old technologies in an aircraft development program, both new and old designs must be evaluated for the continued value of a particular design solution including the continued airworthiness of the systems. As past designs for lightning protection have required basic lightning current flow solutions in part, because of the use of metallic structures, little emphasis has been on the continued availability of these design features until just recently. Recent designs using advanced materials such as composite structures and highly integrated systems require more critical electrical bonding designs which also raise the awareness of the long-term effectiveness of these new designs.

The beginning of this thesis exercise will evaluate related regulations and the certification processes for lightning protective systems as a platform for further evaluation of a potential new design methodology. Part of the certification requirements is to submit "Instructions for Continued Airworthiness (ICA)". Past aircraft certification programs relied on the development of these ICAs in part through an industry Maintenance Steering Group (MSG) organized under the US Air Transport Association (ATA) in the 1970s. This MSG process uses logic that relies on the inherent reliability and safety of each system design as required by FAR 25.1309. In performing MSG analysis, scheduled maintenance recommendations are created that take full advantage of the design intent and maintains the inherent reliability designed into the aircraft systems.

The standards for incorporation of sophisticated protective systems that ensure no single event can result in a catastrophic condition are directly applicable to lightning protection features. Though the MSG process for development of large transport category aircraft maintenance programs has been in existence since the early 1970's, it is only recently that this process has been applied to lightning protection. Past continued airworthiness of lightning protection was provided by non-scheduled maintenance of aircraft protective systems such as lightning diverter strips on an aircraft radome and careful return-to-service procedures including ensuring electrical bond are functional. The use of metallic structure and low-tech avionics gives reason not to have been concerned with a more sophisticated approach to continued airworthiness development.

Compounding the clear way forward to certification is the application of already developed regulations like FAR 25.1309 that ensures all aircraft systems are evaluated for appropriate levels of aircraft safety. What is of interest is the lack of clearly written applicability to lightning protection systems within the guidance for the failure hazard assessment criteria written in FAR 25.1309 used to assist in designing robust and safe systems. One argument for this may be that the lightning protection is typically not determined to be a system. Further investigation to the impact of this definition of systems is researched in detail later in this thesis.

1.2 Research Focus and Background

This thesis recommends a new design methodology that will improve performance, optimize lightning protection design, and deliver Instructions for Continued Airworthiness solutions *that are acceptable to the administrator.* This is achieved by establishing a target for the life of the lightning protection and understanding in detail, the expectations of the administrator through careful assessment of the regulations that result in acceptable certification plans which drive the final design. Current research leading to this body of work builds on the new methodology for lightning protection maintenance determination implemented in 2007 through the US Air Transport Association (ATA). The ATA recommendations contained in the Maintenance Steering Group (MSG-3) document guidelines were revised in 2007 to more effectively address development of lightning protection initial minimum schedule maintenance programs. In these new guidelines, the concept of lightning protection component degradation within the component installed location is used to estimate the robustness of a lightning protection component over the life of the aircraft. This concept of design degradation evaluation is central to the new design methodology proposed within the body of work and captured within this thesis. Aircraft electrical and electronic systems are designed such that no single lightning event can cause or contribute to a catastrophic condition as directed by FAR 25.1316. Aircraft structures have a similar requirement to ensure that no single lightning event can result in a catastrophic condition as defined in FAR 25.581. Past airplane programs have designed redundancy within the lightning protection, but have not achieved full credit for this redundancy due to the threat of the "common mode failure". Without an accepted methodology for minimizing the catastrophic implications of a common-mode failure, ICAs must be developed without critical analysis of the design degradation modes resulting in maintenance of redundant systems simply because these lightning protection components protect against the potentially adverse effects to a critical aircraft system. The reason for needing a more advanced lightning protection design methodology stems partially from the advancement of integrated aircraft systems and use of less electrically conductive aircraft structures. Starting with the advancement of full electronic controlled aircraft such as the Boeing 777, a best guess method combined with statistically insignificant in-service testing was used to satisfy the FAR 25.1529 requirements for continued airworthiness.

In-service testing by the aircraft manufacturer was instituted in the late 1990s as a measure to address redundant lightning protection components that protect multiple systems, due to the highly integrated nature of the systems which may allow a single lightning strike to affect multiple critical systems simultaneously, if not maintained per the type design. The lack of an effective methodology to ensure that these lightning protection components would not degrade to a point of exposing the aircraft to the potentially adverse effects during a lightning strike led to a quandary of inefficient and overly conservative lightning protection maintenance programs in the 1990s. Even though it is understood that aircraft systems have common mode failures for which redundancy minimizes maintenance, the industry found itself unable to manage effective selection of particular lightning protection maintenance. This body of work examines a potential solution to designing lightning protection systems by including the continued airworthiness discipline at the front of the design cycle. This results in more manageable and effective lightning protection product while producing an equally effective set of instructions for continued airworthiness.

1.3 Research Objective

Research objectives summary:

1. Identify, discuss and apply regulations guidance for lightning protection design and continued airworthiness
2. Define lightning protection systems, components and devices and the lightning phenomenon
3. Research lightning events and impacts on aircraft airworthiness
4. Prove gap in design methodology to address continued airworthiness
5. Establish new design methodology to address continued airworthiness
6. Technically evaluate a variety of lightning protection systems
7. Test the methodology
8. Create practical method to develop large scale lightning protection systems continued airworthiness designs

9. Expand test case to include actual design data on multiple and varied existing aircraft lightning protection systems
10. Assess outcome of design methodology to the benefits of aircraft designs
11. Identify future development opportunities and future work that supports this body of work

The body of work conducts several necessary design evaluations in order to evaluate a new industry methodology to address new and existing lightning protection technology. The definition of a "system" is explored to assess if lightning protection "systems" are (or should be) treated differently than current critical and essential systems. Different lightning protection components were selected and evaluated with the design methodology to determine the methodologies viability across different types of protection. Actual data was used and is contained in an Appendix to exercise the methodology and produce valuable knowledge about the design methodology while also protecting the proprietary nature of the data. Application of design requirements for structure, without concern for lightning protection continued airworthiness is contrasted against lightning protection requirements that are integral to structural component design processes. Having assessed the proper application of lightning protection design assessment in the certification of new aircraft technologies, this research and development will also assess regulatory accountability as applied to lightning protection across both systems and structures, thus developing a "basic understanding" of how lightning protection is viewed by the regulations. Feedback from regulators will be included in the studies where appropriate. Once a lightning protection design is evaluated for its specific make-up and installation of the protection, these studies will define a new methodology to develop systems and structures designs that optimize compliance to regulations for the continued airworthiness of lightning protection and produce superior design solutions in comparison to past methods. Failure modes for lightning protection are not the same as the failure modes of the systems in which they protect, given that failure of the lightning protection in combination with a lightning event can affect the system but not necessarily affect the lightning protection. Lightning protection, for the most part, is passive (though some new technologies are deploying active lightning protection systems). In that case, it is not reasonable to manage lightning protection continued airworthiness by associating the effects of system failure to the lightning protection degradation or failure, since the system failure does not necessarily imply a lightning protection failure has occurred. In fact, it may be difficult to determine the definition of a failed lightning protection component since degradation may be present, but the result to the system it is protecting when a lightning event occurs may have no impact to system performance.

In short, lightning protection has been incorporated on classic and advanced technology aircraft in compliance with regulations. New expertise for this area of study is appropriate to improve both the designs and continued safe and economic operation of lightning protection.

1.4 Research Method

Initially, regulations were to be researched to determine the intent of the lightning protection design functions. This will require further investigation of lightning impacts on aircraft and lightning phenomenon. The thesis contains a chapter that describes lightning creation and lightning attachment to aircraft. This section will also provide data gathered from this research on the environment in which lightning is created and the altitude, weather conditions, time of year and temperatures in which lightning strike to aircraft has been reported.

The initial methodology was to be drafted with focus on the lightning protection design component characteristics. The later version of the methodology will be contained in this thesis to include the use of test data and installation location environments to determine environmental threats to the lightning protection survival index. The idea that is leveraged in this design methodology includes understanding of the lightning current electrical conductive paths and brings focus to the long-term survivability of the lightning protection path given the elements that cause degradation within that installed environment.

The new design methodology was to be developed to provide guidance to aircraft designers on how to design lightning protection components to perform effectively over the life of the aircraft. To do this, design goals were to be created and inputs and outputs to the design methodology developed as the methodology matured. Once the methodology reaches maturity, the methodology will be exercised through use of an assessment sheet that will be developed by the student specifically to test the design method practicality. In this approach, an assessment sheet is raised for each lightning protection component. In practical application, this assessment sheet could be implemented by a computing system that integrates different design expertise into a single collaborative tool.

Validation of the methodology was to be gained by use of actual design data from a lightning protection component manufacturer. Though this data was not quite as detailed as that data used in the case studies, the data should provide validation that this methodology could be practically applied to lightning protection designs. The validation could also provide a means to exercise the assessment sheets and improve on the data required to perform a useful assessment.

An extensive series of case studies should be created to test the application of the methodology to real design implementations. The case studies will be developed with proprietary information under contract between the University and the aircraft manufacturer and will be held in a Proprietary Appendix to this thesis.

The discussion to be included in the case studies will evaluate the results and provide detailed comments on the findings. This includes the association of the assessment sheets to the methodology and the connection of the methodology to the aircraft lightning protection design activity.

Finally, the body of work summarized in this thesis will provide conclusions and recommendations for the design assurance of aircraft lightning protection systems continued airworthiness. In this section, the evidence of newly gained knowledge will be presented and follow-on to further work is described.

The chapters used to document the body of work to be included in this thesis will be as follows:

1. **Introduction** - Provide the outline of the work to be conducted, the research method to be used, and the objectives of the works including a problem statement, the regulatory environment, and scope of the studies
2. **What is Lightning** - Describe the phenomenon of lightning, how lightning attaches to aircraft, lightning statistics, aircraft strike data, and how an aircraft is protected from lightning
3. **Methodology** - Develop a design methodology to address the declared need for a new methodology, distinguish the proposed methodology from current methods, meet the research objectives, and provide an implementation solution for the new methodology
4. **Validation** - create a test case to validate the methodology, create and exercise design assessment sheets, and adjust the methodology based on findings
5. **Case Studies** - Exercise the methodology using actual aircraft design data and recommend revised design practices
6. **Lessons of the Case Studies and Revised Methodology** – Provide a critical evaluation of the case studies findings, its practical application and recommend methodology revisions as applicable
7. **Discussion** – Provide a comparison of the objectives to the outcome of the case studies, identify what gaps are filled by use of new methodology and who and how it should be used
8. **Conclusions and Recommendations for Further Work** – Provide summary of key findings in discussion section and future work that should be performed.

1.5 Conclusion of the Problem Statement

The problem statement for this work points to a complex design methodology that is focused on lightning protection. As continued airworthiness requirements for lightning protection are highly interpreted during the time a new aircraft is developed, the use of a methodology to address the need for lightning protection continued airworthiness designs is required to move the industry forward. The use of the methodology will be tested with a validation, evaluated by direct use demonstrated by several case studies, matured through the body of work development process over five years and finally concluded by identifying future work. The methodology developed for these studies has been recognized as valuable work to the manufacturer who has supported this work and has submitted the methodology as a new invention idea to the US Patent Office which is in status “Patent Pending” as of the completion date of this thesis.

Chapter 2 Lightning Characteristics and Impacts on Aircraft

2.1Regulations and Guiding Documents

One of the early objectives was to understand the regulations and guiding principles involved in the creation of current lightning protection continued airworthiness designs. In order to achieve an initial understanding, it was determined to be prudent to evaluate and summarize the Federal Aviation Regulations related to lightning. This section of the introduction chapter proceeds to provide as best possible, an overview of regulations. Also note that during the time this body of work was in development (2005-2010) new guidelines for maintenance determinations of lightning protection systems were published in MSG-3 ATA guidelines document and also HIRF SAE Aerospace Recommended Practices (ARPs) were developed and published through an SAE subcommittee. These changes demonstrate the dynamics of this subject.

Since the application of the regulations is part of the driver that creates impetuous for lightning protection continued airworthiness designs, it is considered appropriate to perform regulation research. Before the technical review was initiated, extensive research into the regulations and existing guidelines was performed starting in 2005. Since then, in 2007 MSG-3 guidelines for the development of lightning protection scheduled maintenance were published having a significant impact on the premise of this work. Key to successful development of Instructions for Continued Airworthiness for lightning protection is the understanding of regulations and industry guideline developments. This contemporary progression in regulation and guideline development during the development of this methodology translated into significant relevance for this body of work. More about regulations and certification processes will be included in the case studies. In the following paragraphs, the research results of regulation and other guiding document are documented to in order to set the scene for this body of work.

Assessment of the regulations and guiding documents are made in order to provide a view of the state of the industry and its impact with regards to appropriate direction for designers to implement safe and economic lightning protection designs including design optimization.

2.1.1 Instructions for Continued Airworthiness (ICA) and FAR 25.1529

The purpose of ICAs is to provide assurance as required by the regulating authorities that the inherent safety of operation determined through type certification of the aircraft will remain in place throughout the life of the aircraft. Instructions for Continued Airworthiness are a critical element of the Certification Plans. This is accomplished through development and delivery of maintenance and operational documents. Demonstrating compliance with these regulations is a requirement for successful airplane certification and delivery. Regulation 14 CFR 21.50(b) states that the holder of design approval, including either the type certificate or supplemental type certificate for an aircraft shall furnish at least one set of complete Instructions for Continued Airworthiness, prepared in accordance with Sections 25.1529 of the regulations. This is required to be supplied to each owner of each type aircraft upon its delivery, or upon issuance of the first standard airworthiness certificate for the affected aircraft.

As aircraft are designed and system safety analyses are developed, the ICA required for successful type certification of an aircraft are also created. In 1980 the final rule for FAR 25.1529 Instructions for Continued Airworthiness was approved by Docket Number(s) 14779 and 14324 in the US Federal Register on September 11, 1980. The purpose of ICA is to ensure that the inherent safety and reliability of the original design is maintained throughout the life of the aircraft.

One of the lists of documents that make up the Instructions for Continued Airworthiness (ICA) is the scheduled maintenance requirements delivered to regulators in a Maintenance Review Board Report (MRBR). Unscheduled maintenance instructions are provided in technical manuals and also submitted for the certification of the aircraft type design. In order to develop the initial minimum scheduled maintenance requirements, working groups are established under an ATA process called MSG-3 (Maintenance Steering Group) that include experts from operators, manufacturers and regulatory authorities to evaluate lightning protection designs and recommend appropriate maintenance requirements. This process is detailed in Advisory Circular AC 121-22A Maintenance Review Board Procedures.

In order to gain the type certification sought aircraft manufacturers must establish how compliance with FAR 25.1529 is achieved at the time of aircraft type certification. The Federal Aviation Regulation Section 25.1529, titled Instructions for Continued Airworthiness states: “The applicant must prepare Instructions for Continued Airworthiness in accordance with Appendix H to this part that are acceptable to the Administrator. The instructions may be incomplete at type certification if a program exists to ensure their completion prior to delivery of the first airplane or issuance of a standard certificate of airworthiness, whichever occurs later.” [Amdt. 25-54, 45 FR 60173, Sept. 11, 1980].
This FAR 25.1529 as applied to lightning protection features must be interpreted by the aircraft manufacturer and compliance is negotiated between the manufacturer and the approving authority for how compliance will be achieved.

In order to establish these instructions, electromagnetic effects engineers and maintenance engineers collaborate to develop appropriate maintenance tasks and maintenance requirements to ensure that the continued airworthiness of the protective systems are maintained throughout the aircrafts operating life. Past lightning protection certification programs have focused on the protection of wire shields, connector grounding, and electrical bonding. New generation aircraft composed primarily of composite materials include additional protection schemes that may require maintenance to ensure that the continued airworthiness of the lightning protection components is maintained. With this evolution of protection design, a methodology associated with the evaluation of maintenance requirements for these new protection designs also evolved as the new MSG-3 guidelines were implemented in 2007.

Certification plans are developed by the manufacturers engineering representatives and delivered to the regulator to certify the aircraft type design. The certification plan provides information on the specific areas of protection required by the regulations and identify the associated means for compliance to the regulations cited. Certification deliverables can also be listed in the Certification Plan that might include references to other document deliverables for lightning protection designs such as test plans, test reports, and a protection assurance plans. More details on protection assurance plans are included later in this thesis. Evidence of compliance to FAR 25.1529 “Instructions for Continued Airworthiness” may also be included in the certification plan to ensure that the lightning protection is adequately maintained. This approach ensures that the aircraft meets its certification basis throughout the life of the aircraft.

2.1.2 Design Regulations FAR/JAR

The following regulations affect the design of lightning protection. Compliance to these regulations can be achieved through many different means and can involve as many different design solutions. Requirements are created on an aircraft development program partially by observance of these regulations. Once negotiated with the certificating authority, the requirements stabilize and focus is then applied to the design solutions.

Some regulations are specific to lightning protection while others such as FAR 25.1309 directs the designer to comply with many different potential events that may impact safety, including lightning as a potential cause of the event. Tables 2-1, 2-2 and 2-3 contain a collection of regulations that may impact lightning protection design. This data is part of the literature research.

In addition, other guiding documents such as Advisory Circulars, ARINC specifications, Military specifications and SAE Aerospace Recommended Practices all may play a role in the design of lightning protection. In past years the use of Special Conditions (I.E. Issue Papers) also drove requirements to meet certain safety criteria where the current regulations at the time were considered inadequate to address new and novel aircraft designs.

The question of new and novel designs has been the center of debate and activity between aircraft manufacturers and the regulatory authorities. Administrators will issue special conditions in cases where sufficient guidance is not provided in currently approved regulations and the need for a specific direction with regard to new or novel designs is deemed by the certifying authority to be prudent.

In the Federal Register: September 11, 1980 (Volume 45, No. 178)][Page 60154] several commenter’s objected to proposed Sec. 21.16(a) which would delete reference to a "novel and unusual design feature" as a necessary condition for the Administrator to issue special conditions. Special conditions become a part of the designated applicable regulations for type certification of a particular product (aircraft, aircraft engine, or propeller). One commenter indicated that the proposed revision is unjustified and would lead to indiscriminate rule making and that instead of simplifying the administration of the requirements it would introduce complexity. Another commenter claims that adoption of proposed Sec. 21.16(a) would introduce uncertainty into design requirements.

It was pointed out in this register by a commenter that if Sec. 21.21(b)(2) were to continue to be used to issue special conditions to cover an unsafe design feature or characteristic that is not "novel or unusual," it must be equally applicable to a condition that exists on more than one (earlier certificated) product, further stating that the other products must then have been type certificated using existing rules which did not adequately cover the unsafe design feature or characteristic.

These comments and questions caused the FAA to completely reevaluate its practices in designating the applicable regulations for type certification under Sec. 21.17(a), commonly referred to as defining a "type certification basis." For lightning protection of advanced and highly integrated aircraft, special conditions have been drafted against several aircraft manufacturer aircraft designs to address gaps in the regulations. As this work investigates a design methodology associated with lightning protection, further consideration is prudent regarding the position of the regulating authorities going forward with regard to new and highly integrated aircraft designs.

From the US federal register, Sections 21.16, 21.17, and 21.21, taken together with FAA policy in designating the applicable regulations must recognize and balance four important considerations: (1) the FAA has an obligation under Section 601 of the Federal Aviation Act of 1958 to keep the airworthiness standards of this subchapter (i.e., FARs 23, 25, 27, 29, 31, 33, and 35) as current as practicable; (2) the type certificate applicant has a right and a need to know, in very specific terms, what the applicable airworthiness standards will be in order to finalize the detail design of its product and to enable the applicant to make reasonable performance guarantees to its potential customers; (3) in the interests of safety, rapid technological advances presently being made by the civil aircraft industry require that the FAA be able to issue special conditions to address truly novel or unusual design features that it has, as yet, not had an adequate opportunity to envisage in the airworthiness standards through the general rulemaking process; and (4) because the airworthiness standards of this subchapter are intentionally objective in nature to allow flexibility in design, the FAA must retain the prerogatives both to make equivalent safety findings and to deny a type certificate whenever an unsafe design feature or characteristic is found during the type certification process.

It must be recognized that in some areas which will vary from time to time the state of the regulations may somewhat lag the state of the art in new design because of the rapidity in which the state of the art is advancing in civil aeronautical design and because of the time required to develop the experience base needed by the FAA to proceed with general rule making. Applicants for type certification of a new design have the opportunity to mitigate the impact of not knowing the precise airworthiness standards to be applied for "novel or unusual design features" by consulting with the FAA early in their certification planning when such features are suspected or known by the applicant to exist. Because of the intentional objective nature of the airworthiness standards, many new design features which might be thought of as "novel or unusual design features" may already be adequately covered by existing regulations, thus obviating the need to issue special conditions.

Since the development of new highly integrated aircraft and with extensive use of composite materials in transport category aircraft, it is important to note at the beginning of this body of work that the design criteria to meet the intent of the administrators are very dynamic as interpretation of what is required is provided in real time during the certification program. The methodology proposed by this body of work calls for integration of design requirements that should not be considered in isolation from the changing regulatory environments, especially in cases where the new aircraft design may be considered novel.

The regulations within the following tables were determined to have a bearing on the proposed methodology but not in a way that would result in changing the proposal at this time. The interpretation of regulations at the time of the design development may result in changes to the methodology, therefore the methodology proposed is considered general in its application.

FAR/JAR reference	Title	Issue Date	Subject
25.581	Lightning Protection	04/01/70	The airplane, including metallic and non-metallic components, must be protected against the catastrophic effects from lightning
25.1316	System Lightning Protection	04/20/94	The electrical and electronic systems whose failure can contribute to or cause a condition that would prevent or reduce continued safe flight and landing must be protected against the effects of lightning.
25.981	Fuel Tank [Ignition Prevention]	Amdt. 25-102, Eff. 6/6/2001	No ignition source may be present at each point in the fuel tank or fuel tank system where catastrophic failure could occur due to ignition of fuel or vapors.
25.954	Fuel System Lightning Protection	9/10/67	The fuel system must be designed and arranged to prevent the ignition of fuel vapor within the system due to lightning.
25.1529 Appendix H*	Airworthiness Standards, Instructions for Continued Airworthiness	Amend 9/11/80	The manufacturer must provide instructions for continued airworthiness that area acceptable to the regulator. *FAR/JAR 25.1529 is not restricted to lightning and HIRF but is interpreted to be applied across the entire aircraft.

Table 2-1 Regulatory References Affecting Lightning Protection

ARP Reference	Title	Issue Date	Subject
ARP5583	HIRF Users Guide	03/01/01	Instructions on how to design and maintain HIRF protection.
ARP5577	Aircraft Lightning Direct Effects Certification	2002-09	Guidance for a means to show compliance with regulations for protection against lightning direct effects for aircraft of conventional design and advanced composites.
ARP5412	Aircraft Lightning Environment and Related Test Waveforms	1999-11, Revised 2005-02	Provides waveform and environmental data and analysis currently available.
ARP 5413	Certification of Aircraft Electrical/Electronic Systems for the Indirect Effects of Lightning	1999-11	Guidance for showing compliance with the regulations for hazards caused by lightning environment to electrical and electronic systems.
ARP5414	Aircraft Lightning Zoning	1999-12 2005-02	Defines lightning strike zones and provides guidelines for locating them on particular aircraft and also provides examples.
ARP 5415	User's Manual for Certification of Aircraft Electrical/Electronic Systems for the Indirect Effects of Lightning	2001-08 2002-04	Provides information for 1) Acceptance criteria for indirect effects of lightning 2) verification analysis and test methods 3) recommended design options to optimize needed system immunity to indirect effects.
ARP 5416	Aircraft Lightning Test Methods	2005-03	Describes how to conduct lightning direct effects tests and indirect system upset effects tests.

Table 2-2 SAE Aerospace Recommended Practices affecting lightning designs

Advisory Circular Reference	Title	Issue Date	Subject
AC20-136	Protection of Aircraft Electrical/Electronic Systems Against the Indirect Effects	3/5/90	Provides guidance on how to comply with the requirements of FAR/JARs relating to protection of aircraft electrical/electronic systems installed either on or within an aircraft from the effects of lightning.

Advisory Circular Reference	Title	Issue Date	Subject
	of Lightning		
AC20-53A	Protection of Aircraft Fuel Systems Against Fuel Vapor Ignition Due To Lightning	4/12/85	Provides guidance to means but not only means for compliance to FAR/JARs applicable to the prevention of fuel vapor due to lightning.
AC20-107A	Composite Aircraft Structure	4/25/84	Provides guidance to demonstrate that composite structure provides an acceptable means for diverting electrical current as a result of a lightning strike so as not to endanger the aircraft.
AC25-981-1B	Fuel Tank Ignition Source Guidelines	4/18/01	Provides guidance for demonstrating compliance with certification requirements for prevention of ignition sources within the fuel tank including guidance on lightning as an ignition source.
AC25-981-2	Tank Flammability Minimization	4/18/01	Provides guidance for compliance to airworthiness standards pertaining to minimization of hazards from flammable fuel air mixtures within fuel tanks.
AC121-22A	Maintenance review Board Procedures	3/7/97	Provides guidance that can be used during development and revision of the initial minimum scheduled maintenance/inspection requirements for a derivative or newly type-certified transport category aircraft for submittal to the FAA for approval

Table 2-3 Advisory Circulars impacting lightning design and maintenance

2.2 What is Lightning?

Lightning is the dissipation of static energy stored in cloud clusters. Scientists believe that the static energy stored in clouds comes from the relative motion of precipitation within the clouds that generate free electrons resulting in stored charges collected within the cloud. Positive charge in the cloud will seek negative charges on the earths' surface. While in the same manner, negative charges in the cloud will seek positive charges on the ground. Lightning begins to move away from the cloud filled with static energy in what is called leaders. Leaders are electrical energy moving out to seek ground or an object of opposite charge. Leaders stem from what is called a lightning channel. Lightning energy moves from the lightning channel in leader streams. As the leaders find nowhere to transfer energy in an opposite charge or "ground" the leader is drawn back into the channel and the channel stores the leader charge which increases the energy in the leader channel. Again leaders stream away from the lightning channel seeking an opposite charge.

This process continues while the lightning channel grows until a leader finds an oppositely charged object and quickly discharges the energy built up in the channel. This transfer of channel energy can be dramatic since the stored plasma often reaches incredible levels of electrical power beyond 1 million volts and reach temperatures of 50,000 degrees Fahrenheit. From the picture in Figure 2-1 below, lightning channels can be easily identified by the thick white lines while the leaders are recognized by the thinner less bold lines attached to the channel.

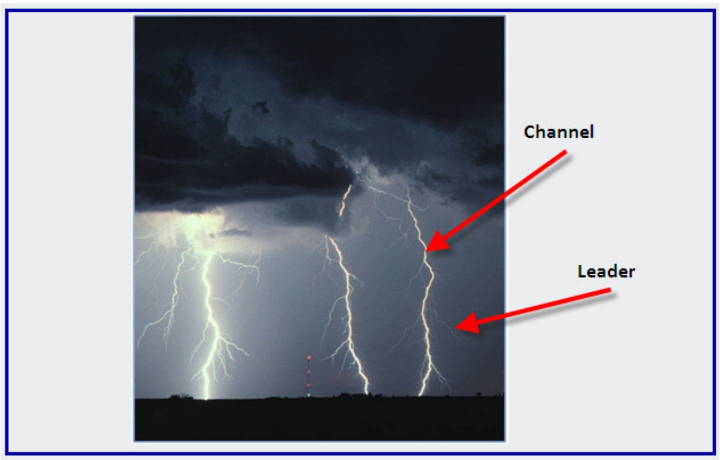

Figure 2-1 Lightning channels and lightning leaders

As demonstrated in the Figure 2-2, lightning can strike from the ground to the cloud or from the cloud to the ground. Lightning also strikes between clouds, from the cloud top up and from the cloud in a parallel direction to the earth. Energy stored in lightning clouds can be amazingly large. According to Fisher, Perala and Plumer [2.2], lightning clouds may store energy with a potential relative to the earth of 10E8 to 10E9 volts. For more physics of lightning, see "Lightning" by M.A. Uman [2.1]. Aircraft are struck by lightning through different means, often initiating the lightning attachment to the aircraft extremities. What we know about lightning strikes to aircraft and the models for lightning energy and waveforms used in aircraft design comes from tests on one aircraft in the 1960's and 3 aircraft in the 1980's using aircraft instrumented with electrical measurement devices. Lightning has the potential for serious impact on aircraft operations. According to some aircraft manufacturers, damage to aircraft struck by lightning can create down time for repair of 1-3 days for common lightning strikes. In order to understand the issues associated with the interaction of lightning and aircraft it is important to explore how aircraft get struck by lightning.

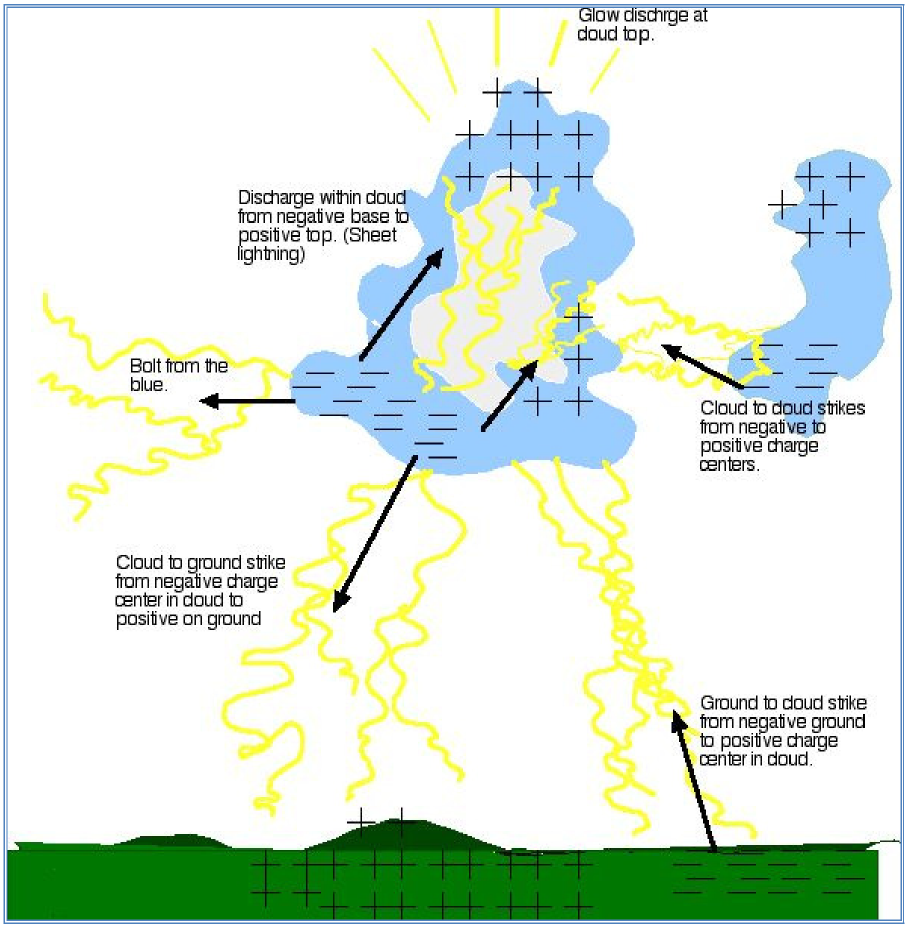

Figure 2-2 Lightning Phenomenon

2.3 How do Aircraft get Struck by Lightning?

Lightning strikes aircraft on the ground and in the air. It has been recorded that aircraft can get struck by lightning even when not in obvious storm conditions. Aircraft lightning attachment experts note that aircraft are struck by both moving through a lightning strike already in progress and also by triggering lightning. In the 1980's, with extensive testing (sponsored by NASA) of lightning strike to aircraft phenomenon, it was demonstrated that a vast majority of lightning strikes to aircraft are initiated by the aircraft. It is estimated that well over 90 percent of aircraft lightning strikes are "triggered". Prior to completion of more detailed studies, it was believed that aircraft were struck by lightning by flying through and intercepting a discharge that was already in motion. During this time, pilots would argue that lightning was caused by moving aircraft since their observations revealed that lightning strikes the aircraft near clouds even when there are no visible lightning events observed in the nearby cloud clusters. It is a known fact that lightning can strike miles away from a thunderstorm.

Aircraft get struck by lightning by simply flying through electromagnetic fields and creating the right conditions for breakdown. Research shows that it is the saturation of electromagnetic fields in airspace that create the opportunity for breakdown voltages to occur. At sea level, voltages that are maintained long enough at an average voltage gradient of 500kV/m almost always result in breakdown of an electrode gap. At 6000m altitude voltages of 250 kV/m cause breakdown of the air gap. Thus aircraft flying in conditions of 250 kV/m or more are at risk of becoming a part of the lightning strike event. Researchers of lightning phenomenon have confirmed through several means that fields of between 250 to 500 kV/m occur in clouds naturally. Earlier writing identifies that aircraft flying through a moderately strong E-field region can trigger lightning. For small aircraft (20m long), ambient fields of at least 50kV/m are required and less for larger aircraft [2.6]. As an aircraft travels through electromagnetic fields, studies by NASA revealed that the fields at the nose of the aircraft were enhanced by a factor of about ten, fields at the tips of wings are enhanced by a factor of seven, and fields at the tip of the stabilizer are enhanced by a factor of three. With the combination of increased field densities around extremities of the aircraft and relatively strong existing field densities in the region, lightning can be triggered by the aircraft when the enhanced field exceeds the minimum breakdown strength of the air.

To illustrate a lightning strike to an aircraft the following steps occur. Figure 2-3 illustrates these steps.

1. Aircraft flies directly towards a positive charge center
2. The aircraft becomes polarized in response to the ambient field with one end of the aircraft having a negative charge and the other having a positive charge
3. The ambient field is enhanced by the presence of the aircraft
4. As the aircraft approaches an atmospherically charged region, the fields increase on the surface of the aircraft and compression of adjacent equipotentials occurs.
5. Coronas occur at the aircraft nose and leading edges of the aircraft where ionization of the air takes place due to enhance electrical fields. (Coronas are ionized air space that represent an impending electrical discharge)
6. With a corona now emerging from the aircraft and with sufficiently increasing field strengths, leaders extend form from the nose and tail of the aircraft in opposite directions as the aircraft positive and negative polarities at opposite ends of the aircraft interact with the atmospheric charge.
7. Leaders from the aircraft extremities grow larger as the process continues
8. leaders also emerge from charged cloud centers creating more excitement on the aircraft, increasing the leader extensions more
9. Stepped lightning leaders from the cloud continue to approach the emerging leaders emanating from the aircraft and finally meet the leader extending from the aircraft at the switching point
10. A strike to the aircraft occurs
11. Energy is transferred through the aircraft with potential damage to the entry and exit points (Direct Effects Lightning) and potential interruption of electronic equipment due to induced voltage and current flow on aircraft wires and other metal transport elements e.g. ducts and tubes.

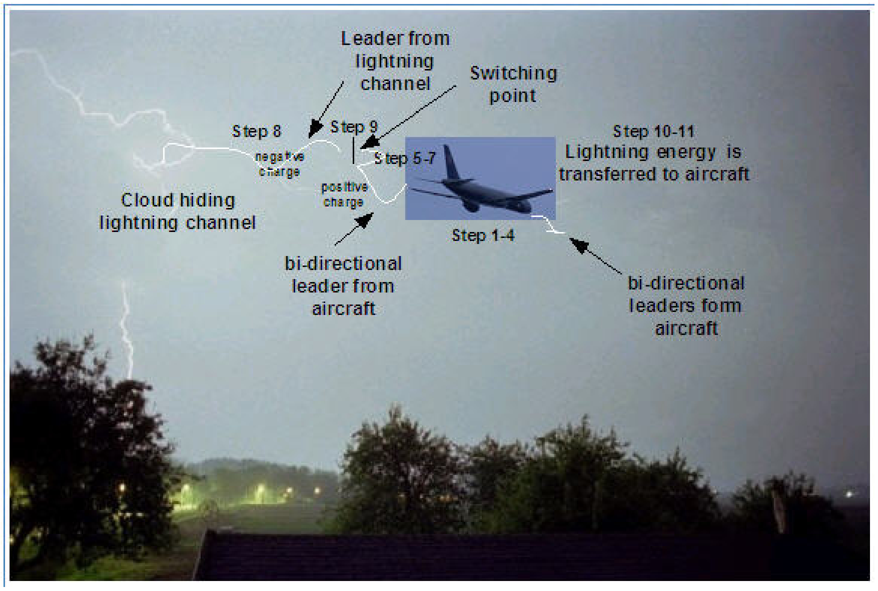

Figure 2-3 Illustration of steps for lightning strike to aircraft

2.4 How often and under what Conditions is an Aircraft Struck by Lightning?

Using data on lightning strikes imaged from a the Optical Transient Detector (OTD) satellite as shown in Figure 2-4, recent research has produced estimates that about 1.2 billion lightning flashes occur around the world per year [2.9].

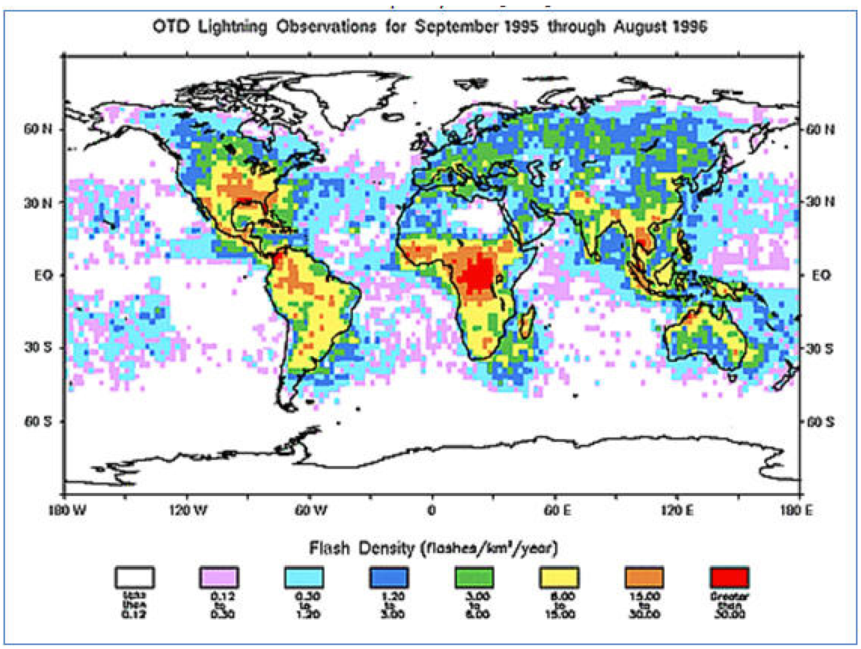

Figure 2-4 Optical Transient Detector satellite data depicting lightning flashes

For aircraft operations in the United States, it is estimated that on average, each airplane in the U.S. commercial fleet is struck about once per year. This figure has been confirmed through research as sited in several articles referenced in this thesis but does not seem to be substantiated since the early 1980s when Lightning Technologies Inc. conducted a specific survey [2.2]. Route structures for commercial aircraft often require aircraft to fly into charged cells activity, raising the probabilities of a strike to occur. In most instances, the lightning flash originates at the airplane and is often visually experienced by the flight crew or passengers. Records of the strike may include maintenance log entries made by pilots after the flight. Although record keeping on lightning strikes is poor, smaller business and private airplanes are thought to be struck less frequently because they usually do not adhere to rigid schedules and flight patterns of large commercial transport aircraft. In a combined data set within Table 2-4 adapted from Fisher, Parala and Plummer [2.2] representing recorded lightning strikes to commercial aircraft from 1950 to 1974, it is noted that lightning strikes occur approximately every 3000 hours of aircraft operation.

Aircraft type	Strikes	Hours	No. Hours per strike
Piston	808	2,000,000	2475
Turboprop	389	1,291,000	3320
Jet	521	1,741,000	3340
All	1718	5,032,000	2930

Table 2-4 Number of lightning strikes to aircraft

Industry research reviewed by the author during research for these studies continues to reference the “one-strike-per-year” criteria. The value of one strike per year extracted from the table is presented with actual data. It is hard to determine in this research whether further studies of actual lightning strike events to aircraft will conclude the same frequency of strikes. Certainly there is an implied difference in aircraft that may fly in more abundant lightning strike regions of the world referenced on Figure 2-4

In reviewing the data, one notes that the number of lightning strikes to aircraft correlates indirectly to the seasons of the year through the presence of precipitation and cloud activity. Most strikes occur at approximately 5000m altitude though it is not unusual to hear about strikes occurring at 12, 000m altitude.

Knowledge of the flight and weather conditions during which aircraft are most likely to encounter strikes are most important to pilots whose interest is in operating safely throughout a flight regime. The following tables describe interesting correlations between aircraft lightning attachments and other meteorological and physical phenomenon. The first correlation in Table 2-5 shows that **more aircraft strikes occur during the aircraft climb** phase of operation than any other operating phase [2.8].

Aircraft operating mode	Number of Strikes	Percentage of Strikes
Departure		
Climb	260	36%
Level	190	26%
Descent	110	15%
Approach	160	22%

Table 2-5 Lightning strikes as a function of aircraft operating segment (adapted from Fisher, Perala, Plumer)

Lightning has also been correlated to presence of precipitation. In a detailed study performed by Lightning Technologies Inc. it was determined that **most lightning strikes were noted during presence of rain representing seventy percent of all lightning strikes occurrences** in the studies [2.8]. All other forms of precipitation in Figure 2-5 (adapted from Fisher, Parala, Plumer)are shown to be between 1 and 5 percent of all lightning strike in the reported data..

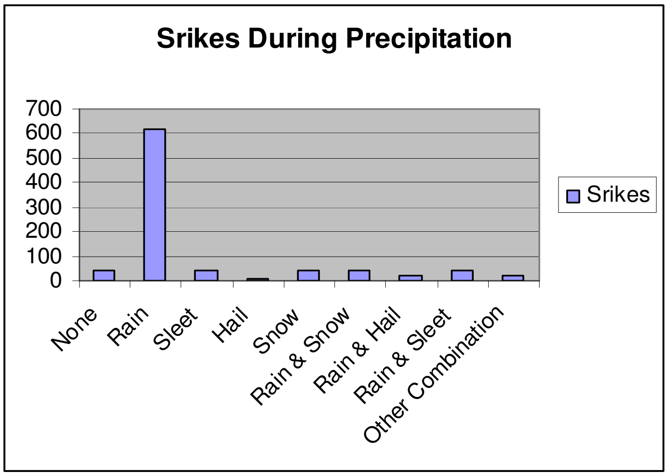

Figure 2-5 Precipitation correlations to aircraft lightning strikes

Lightning strike occurrences in the Plumer study identified approximate strike distribution in accordance with Table 2-6 (adapted from Fisher, Parala, Plumer). This data is also drawn from the aircraft lightning strike study performed by Lightning Technologies Inc. in 2001 [2.8]. The data in Table 2-6 (adapted from Fisher, Parala, Plumer)shows that most strikes occur while aircraft are within clouds.

Cloud Orientation	Percent of total reported
Above	< 1%
Within	96%
Below	3%
Between	< 1%
Beside	< 1%

Table 2-6 Aircraft location during lightning strike event

Lightning strike correlation to altitude depicts that most lightning occurs below 25,000 feet altitude. From the research, the author notes that different data sets describe different distributions with regard to percentage of strikes at specified altitudes. With the data provided adapted from Fisher, Parala and Plummer [2.2], the following distribution is found in strike survey taken on US commercial jets, Figure 2-6 (adapted from Fisher, Parala, Plumer)

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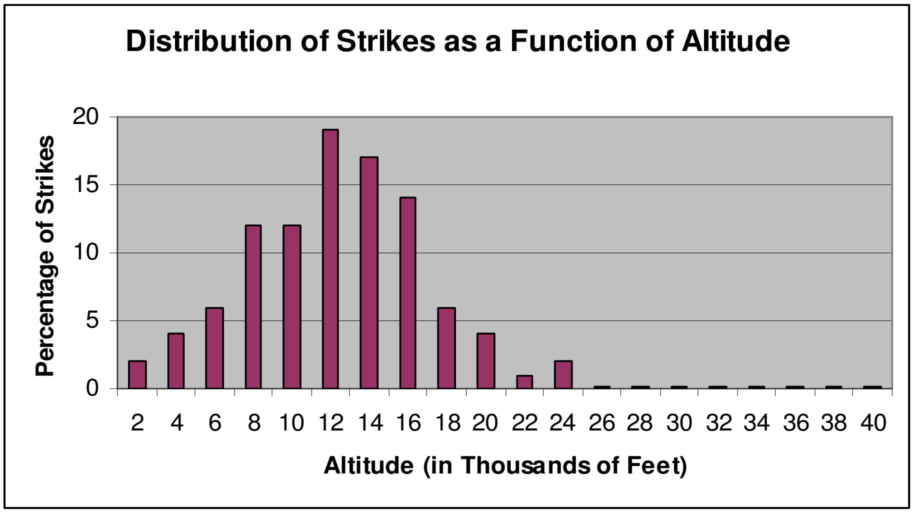


Figure 2-6 Distribution of Lightning Strikes as a Function of Altitude

In further research, the author notes an article in the Lockheed Airline Pilot magazine in November of 1964 that the understanding at this time was that statistics on lightning strikes to aircraft seem to show that altitude plays a minor role as far as determining the likelihood of being struck. About the only conclusion that can be drawn from this source is, **"the probability of lightning strike to aircraft drops sharply above 20,000 feet."** Information gathered in this section would indicate that lightning strike probability does decline above 20,0000 feet however that a more current survey is not available for modeling lightning strike probability.

Temperature has also a relationship to lightning strikes. With data adapted from Fisher, Parala, Plumer [2.2] the following Figure 2-7 is derived based on a study called the Lightning Strike Survey Report for the period of January 1965 through December of 1966 [2.11]. The chart concludes that **there is a strong relationship between temperatures around 0 Degrees C and lightning strikes to aircraft**. This relationship may coincide with the theory that static energy is built up within clouds as a result of freezing and melting precipitation.

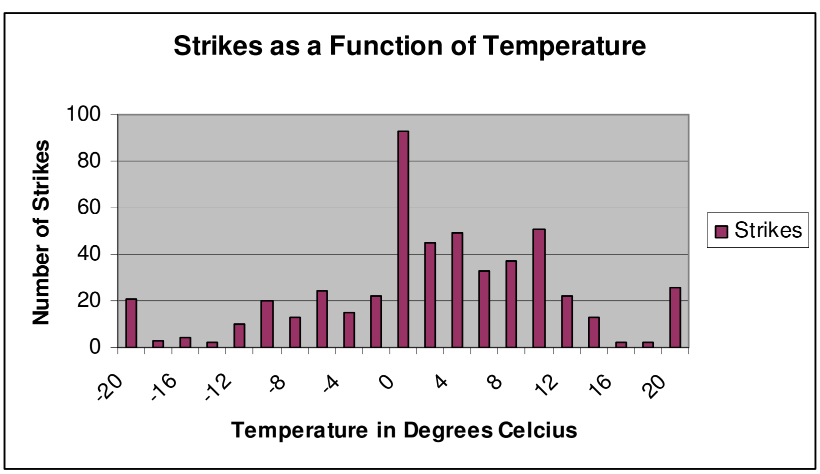


Figure 2-7 Distribution of Lightning Strikes as a Function of Temperature

In order to determine general meteorological conditions that have been noted to coincide with lightning strike frequency, the following data found in Table 2-7 was also collected from meteorological conditions prevailing during 99 United Air Lines lightning strike incidents between July 1963 and June of 1964 [2.10].

Synoptic Type	Percentage of Discharges
Airmass Instability	27
Stationary Front	18
Cold Front	17
Warm Front	9
Squall line or instability line	9
Orographic	6
Cold Low or Filling Low	5
Warm Sector Apex	3
Complex or Intense Low	3
Occluded Front	1
Pacific Surge	1

Table 2-7 Synoptic Types Involved with 99 electrical discharges on United Air Lines Lightning Incident Reports

In summary of the United Air Lines 99 strike report, Harrison points out that any **conditions that cause precipitation, may also be expected to cause electrical discharges**, although he adds that no strikes were reported in the middle of warm front winter snowstorms. It would appear that **spring and summer months are the most likely to create lightning attachments to aircraft.** With regard to the United Airline 99 strike data set, is important to note that **forty two percent of the strike incidents were reported where no thunderstorms had been reported by the pilots**. Thirty three percent of the remaining strikes were reported near thunderstorms and twenty four percent were reported in the general area of thunderstorms.

To corroborate the entire data set, we see that most aircraft lightning strikes occur during takeoff, with raining conditions and clouds surrounding the aircraft most probably at 12,000 feet within an air mass of high instability and at temperatures close to 0 degree Celsius. Research performed by the author to identify weather conditions and orientation during a lightning strike concluded that a central data base does not exist and certain data sets available are quite dated.

2.5 Where Does Lightning Strike?

In order to understand how to defend against the potentially catastrophic effects of lightning strike to an aircraft, one must understand where an aircraft is most likely to be struck by lightning. Lightning strikes are most likely to occur at the aircraft nose, leading edge, tail or wing tips. Typically, lightning energy will move along the aircraft fuselage and exit aft of the initial attachment. It is common to see holes at entry points in the aircraft radome and obvious burn marks along the aircraft rudder where the lightning exited the aircraft. Lightning strikes to aircraft usually occur at transition altitudes either in takeoff or in landing. According to Fisher and Plumer [2.2], only 25% of the aircraft strikes occur during level flight. Plumer and Fisher [2.2] also point out that 75% of all strikes occur between 5000 and 15000 feet altitude. Techniques for modeling lightning strike zones on aircraft have been developed and can be found in SAE Aviation Recommended Practice (ARP) 5414A [2.3]. Aircraft zone definitions are used by EME engineers to assist in defining the lightning threat pattern and are assessed using modeling tools. Different aircraft have different zone maps. “Lightning Zoning” as it is called by engineers, is a fundamental exercise that usually occurs early in an aircraft development program. Guidance for determination of lightning zones is found in the SAE ARP 5414 [2.3]. Lightning strikes can enter and exit at different locations such as wing-to-wing, wing-to-empennage, wing-to rudder, nose cone-to-wing etc. Figure 2-8 (adapted from SAE ARP 5414, Revision A) provides an example of a lightning strike taken on the radome of the aircraft and then swept back by the motion of the aircraft in the air (called “Swept Stroke”) resulting in several other attachments along the fuselage and finally, an exit through the aircraft wing tip and empennage.

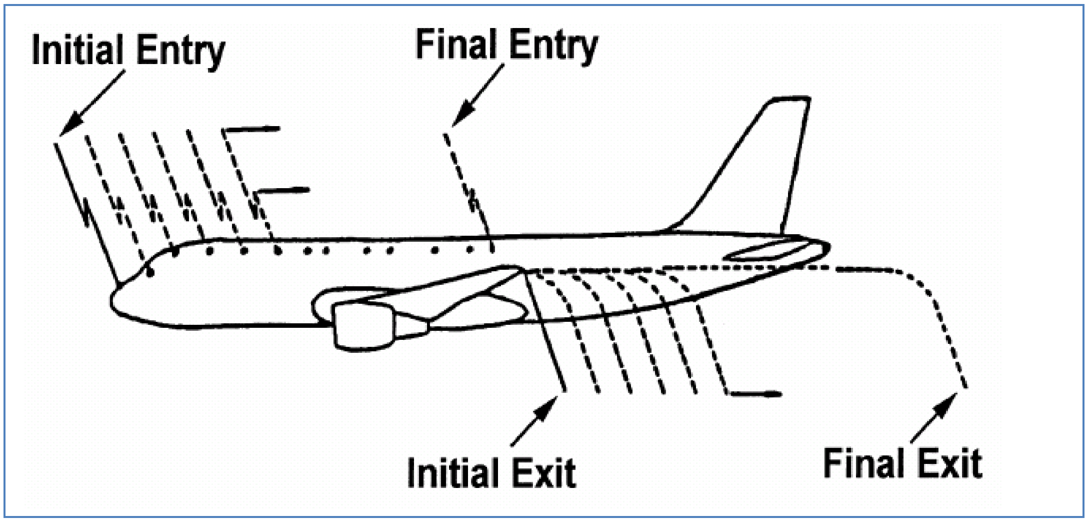


Figure 2-8 Lightning Entry and Exit Points and Swept Stroke Lightning

In order to determine lightning zones on aircraft, ARP 5414 [2.3] defines lightning intensity and areas of most probability as “zones” in accordance with Table 2-8

Zone Designation	Description	Definition
1A	First return stroke zone	All areas of the aircraft surfaces where a first return is likely during lightning channel attachment with a low expectation of flash hang on.
1B	First return stroke zone with a long hang on	All areas of the aircraft surfaces where a first return is likely during lightning channel attachment with a low expectation of flash hang on
1C	Transition zone for first return stroke	All areas of the aircraft surfaces where a first return stroke of reduced amplitude is likely during lightning channel attachment with a low expectation of flash hang on.

Zone Designation	Description	Definition
2A	Swept stroke zone	All areas of the aircraft surfaces where a first return of reduced amplitude is likely during lightning channel attachment with a low expectation of flash hang on.
2B	Swept stroke zone with long hang on	All areas of the aircraft surfaces into which a lightning channel carry subsequent return stroke is likely to be swept with a high expectation of flash hang on.
3	Strike locations other than Zone 1 and Zone 2	Those surfaces not in Zone 1A, 1B, 1C, 2A, or 2B, where any attachment of the lightning channel is unlikely, and those portions of the aircraft that lies beneath or between the other zones and/or conduct substantial amount of electrical current between direct or swept stroke attachment points.

Table 2-8 Lightning Zone Definitions (in accordance with SAE ARP 5414 [3])

The first return stroke of a lightning strike on an aircraft is that the initial attachment to an aircraft surface that creates a closed circuit between the charge center in the cloud and an opposite charge center which is often the earth. Attachment locations on the aircraft are driven primarily by dimensions and shapes of the surfaces. As each aircraft is slightly different in shape, different zones are defined through analysis and test by electromagnetic engineers.

Lightning strike zones are then drawn into the aircraft surface design similar to the example found in Figure 2-9. The map of the aircraft lightning zones created by the aircraft designer is used widely by the entire aircraft design team during an aircraft development or modification program to understand the lightning threat levels and establishes the protection schemes that will be appropriate to protect the aircraft from a catastrophic condition due to lightning.

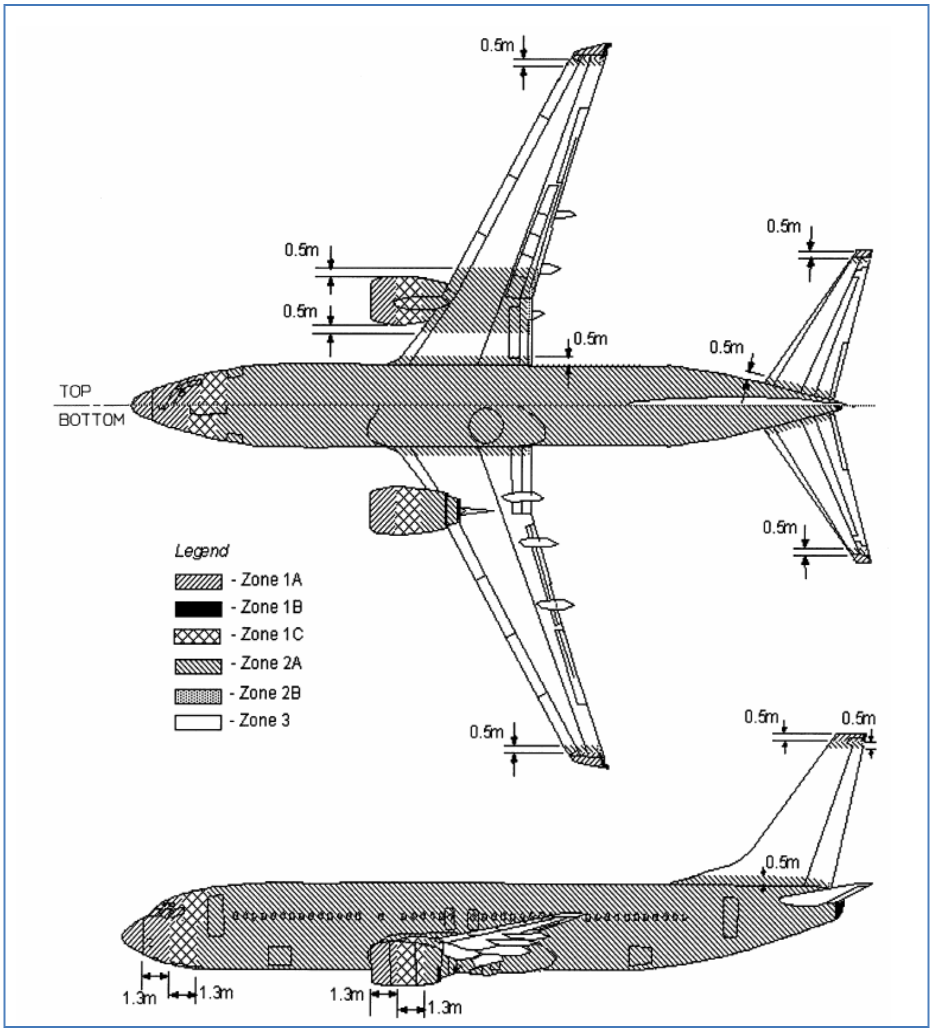


Figure 2-9 Lightning Zones (from SAE ARP 5414, Chapter 2 ref [3])

Calculations within lightning zoning mathematical models developed by the aircraft manufacturers or consultants are one source to identify where lightning strikes an aircraft and how severe the lightning energy transfer is that might be expected. In addition, scale models of the aircraft are exposed to simulated lightning strokes in the laboratory to verify estimates for lightning zones. Similarity to other aircraft geometries are also referenced to develop lightning zones in cases where geometric designs can be declared the same. Though lightning zone determination is a very important part of the design process, aircraft are rarely flown into lightning conditions to "test" the validity of the lightning zones established by the designers.

The chart in Figure 2-10 depicts lightning strikes locations and adapted from "The Airline Pilot" in Nov., 1964 and demonstrates an early understanding of lightning strike locations [2.5]. This early data corroborates data found in the SAE ARP 5414 [2.3] and is verified by experience in the industry with lightning strikes on aircraft.

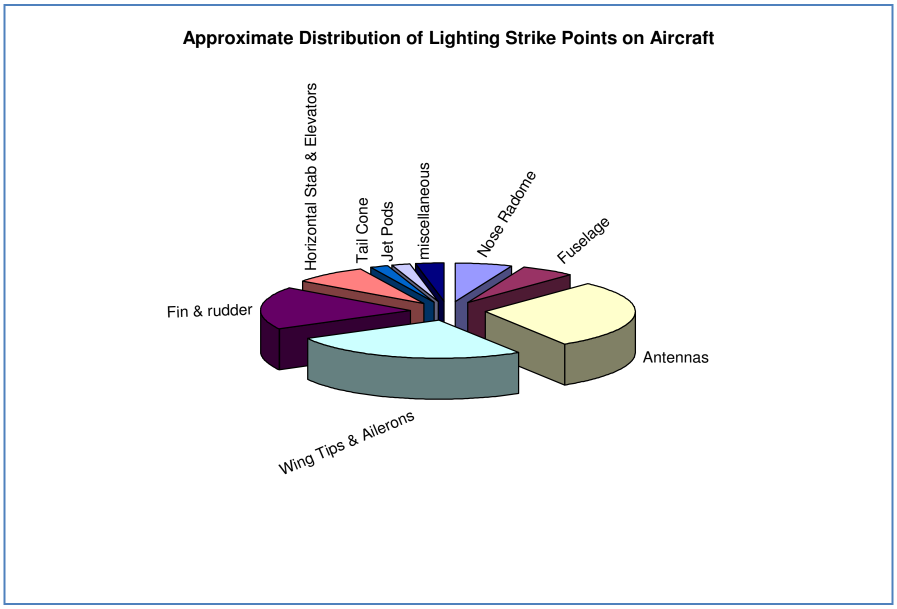


Figure 2-10 Approximate distribution points of aircraft strike locations

Lightning attaches to aircraft most often in the outer extremities of the aircraft with fewer strikes occurring along the fuselage and wing root. These attachment points are also the location of the highest energy transfer. Models have also been created through the SAE committee and are captured in SAE ARP 5412 [2.12] with associated waveforms and lightning threat levels. Typically, a Zone 1 lightning current is 200KA, a Zone 2 lightning current is 100 KA, and Zone 3 lightning current is 30KA.

2.6 What Happens when an Aircraft is Struck by Lightning?

Problems can occur when lightning strikes an aircraft. Unless cloud activity is entirely avoided, lightning strikes to aircraft will occur. Although passengers and crew may see a flash and hear a loud noise, often, nothing serious happens because of the careful lightning protection engineered into the aircraft and its sensitive components. The key to successfully surviving a lightning strike without upset to the aircraft or equipment is to manage the flow of the energy safely around the control electronics or structure and design the lightning conducted energy path such that the effects on the electronics or structure does not compromise continued safe flight. Lightning strikes on aircraft raise the aircraft voltage levels to equal the lightning potential. When the lightning strike ends, the aircraft voltage level falls again to the previous steady state before the strike event. When lightning strikes an airplane, an attachment to external aircraft extremities occurs such as the nose or wing tip. One common occurrence is the sweeping of the lightning across the aircraft fuselage as the aircraft moves through the air. This is called “swept Stroke” lightning. Since jet aircrafts move at speeds beyond their length during a lightning event, entry points may reoccur along the top of the aircraft creating multiple entries. This reattachment is commonly called a “swept stroke”, usually occurring across the top of the aircraft and creating pin holes as the lightning channel continues to reattach to the aircraft in flight. Within this process the swept lightning strokes along the fuselage attach randomly to the fuselage. Once a lightning leader is attached, several things can occur to the aircraft as the energy is dissipated. Entry points are not always obvious, however as the energy discharges from the lightning channel, the energy moves through the aircraft and exits in a different location. This means that lightning currents will flow through the aircraft and are known to take varied paths such as moving along wiring or structural components in the path of the current. The key to good protection design is to make sure that the lightning energy is conducted through the aircraft as efficiently and safely as possible. Differences of potential within the aircraft structure may cause sparking and should be considered during the design of the airframe. Since lightning energy paths cannot be predicted, good lightning protection design includes shielding of critical systems wiring, transport elements that move in and out of the fuel tanks and structural elements where sparks may occur in flammable leakage zones. From a pilots' perspective, occasional reports are written about temporary flickering of lights or short-lived interference with instruments during a lightning event. Sometimes static interference is noted on the communications devices but this is not always related to lightning strikes. Lightning might also attach to a wing tip and exit out a rudder or the other wing tip. These paths need to be understood in order to establish appropriate protection without compromising any performance or safety.

For a long time, the physical damage at the point of lightning attachment was of primary concern. This included holes in the metallic skins, puncture or splintering of non-metallic structures and welding or roughening of moveable hinges and bearings [2.13]. If attachment points are wing tip lights or antenna, the possibility of some lightning current conducting into the aircraft electrical circuits was also considered a concern. Today these physical damages caused by lightning attachments are called direct effects of lightning. Figure 2-11 shows examples of damage to aircraft caused by the direct effects lightning.

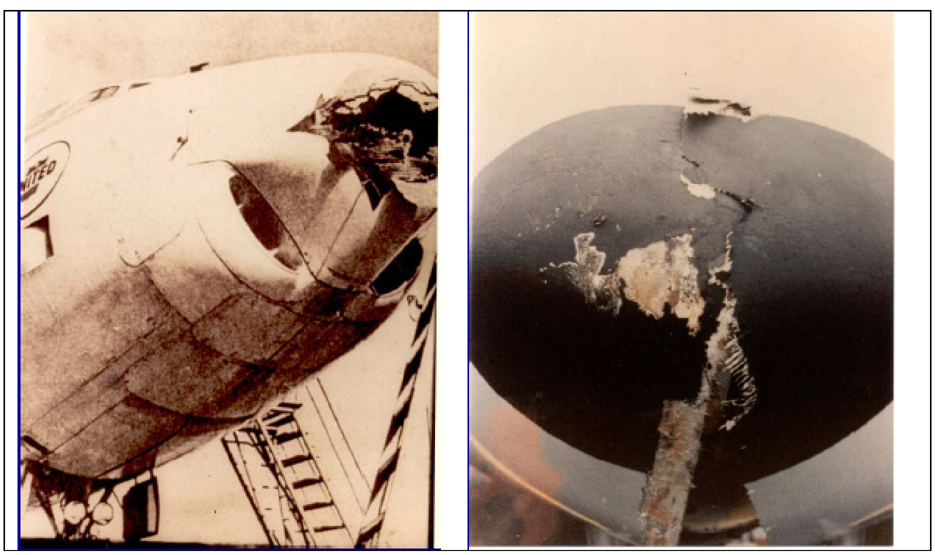


Figure 2-11 Aircraft direct effect damage due to lightning strike in Zone 1A

2.7 Does Lightning Cause Aircraft to Crash?

Edward J. Rupke, senior engineer at Lightning Technologies in Pittsfield, Mass., provides the following explanation: On average, each airplane in the U.S. commercial fleet is struck lightly by lightning more than once a year. In fact, aircraft often trigger lightning when flying through a heavily charged region of a cloud. Business and private airplanes are thought to be struck less frequently because of their smaller size and because they often can avoid weather conducive to lightning strikes [2.14].

The last confirmed commercial plane crash in the U.S. directly attributed to lightning occurred in 1967 [2.14]. Research on this statement could not be verified by the author. Today airplanes receive a rigorous set of lightning certification tests to verify the safety of their designs. Although passengers and crew may see a flash and hear a loud noise if lightning strikes their plane, nothing serious should happen, because of the careful protection engineered into the aircraft.

Aircraft crashes and near crashes are the worst possible outcome for aircraft with inadequate lightning protection. Considering the number of aircraft flying around the world with an estimated 2000 to 3000 thunderstorms taking place at any time somewhere in the world, lightning attachment to aircraft is an unavoidable situation. Most lightning strikes attach to aircraft extremities such as the rudder, nose cone, wing tips and engine inlets. With proper protection, these attachments will not result in an aircraft crash. However, history proves that aircraft crashes do occur resulting from a lightning strike. Lightning related crashes can stem from loss of aircraft control, fuel tank ignition, or pilot blinding during a critical landing phase.

One clear example of a loss of aircraft was in 1963 when a Pan American World Airways 707 was struck by lightning and burst into flames. Seventy passengers and 8 crew members were killed in the crash. Investigation of the crash revealed that the aircraft fuel tanks had exploded. Evidence of lightning was found on the wing tip. The exact mechanism for how the fuel tanks were ignited was not determined [2.7].

In an article written by Michael Cherington M.D. [2.4] data from the National Transport Safety Board (www.ntsb.gov) comprised of 26 years of data (1963 to 1989) identified injuries due to lightning strike on aircraft. In that period, 40 lightning related accidents occurred, 10 involving commercial flights and 30 involving private aircraft, causing 290 fatalities. Of these flights, 4 commercial plane accidents accounted for 260 of the fatalities, and 14 non-commercial plane accidents accounted for the remaining 30 fatalities. Significant accidents are as follows:

1. Pan American World Airlines Boeing 707 plane exploded over Elkton MD on August 12, 1963. The cause of the crash was a fuel tank explosion killing all 86 passengers on board. The NTSB report identifies that lightning was not a probable cause [2.30].
2. Delta Airlines Lockheed L-1011 plane crashed on landing approach to Dallas/Fort Worth International Airport on August 2, 1985. The accident resulted in 135 fatalities and 28 injuries. Though several observers reported seeing lightning hit the airplane, investigators were unable to confirm lightning as the cause of the crash. Lightning is listed as a major factor in the NTSB accident report.
3. US Air McDonnell-Douglas DC9-31 plane was damaged due to a lightning strike. A ground mechanic was fatally injured when he touched the exterior of the aircraft during the lightning strike.

4. Ozark Airlines Fairchild FH227B plane flying over St. Louis, Mo. sustained a direct lightning strike killing all 38 passengers on July 23, 1973.

Since the realization of the potential devastating effects of lightning, much has been learned about how lightning can affect airplanes, and protection techniques have improved. Airplanes receive a rigorous set of lightning qualification tests to verify the safety of their designs and allow for acceptable compliance to lightning certification requirements. Comparable requirements for general aviation aircraft are correlated to commercial transport federal regulations in Table 2-9.

	General Aviation	Commercial Transport
Airframe	FAR 23.867	FAR 25.581
Fuels System	FAR 23.954	FAR 25.954 and FAR 25.981
Other Systems	FAR 23.1309(c)	FAR 25.1309
Electrical and Avionic		FAR 25.1316

Table 2-9 Certification regulations pertaining to lightning protection

2.8 How is an Aircraft Protected from Lightning?

Aircraft are designed with well-developed protection systems. Most aircraft skins are made primarily of aluminum, which is a very good conductor of electricity. By making sure that there are no gaps in this conductive path, the engineer can assure that most of the lightning current will remain on the exterior skin of the aircraft. Some modern aircraft are made of advanced composite materials, which are significantly less conductive than aluminum at low lightning frequencies. In this case, the composites are made with an embedded layer of conductive fibers or screens designed to carry or disseminate lightning currents during a strike event. Damage to structure at the location in which lightning attachment occurs is called direct effects. Lightning protection designs are thoroughly tested before incorporation to aircraft. Some examples of lightning protection:

1. Expanded Aluminum Foil (EAF): used to protect aircraft structure from direct lightning strikes
2. Lightning Insulators (sometimes called Isolators): used to help rout lightning strikes through safe areas of aircraft structures; they are typically used within conventional metal fuel lines and conduits and consist of non-metallic insulator attached either directly onto tube or onto a separable coupling.
3. Lightning Diverters: used to divert lightning from penetrating radome
4. Conductive Metallic Wire Screen: incorporated into prepreg composite layers for lightning strike dispersion
5. Lightning arrestors: used to eliminate spark at fuel tank overflow valves
6. Bond straps and ground points along installations

Lightning direct and indirect effects will be discussed in more depth in the case studies conducted as part of this work. Modern passenger jets have miles of wires and dozens of computers and other instruments that control everything from the engines to the passengers' music headsets. These computers, like all computers, are sometimes susceptible to upset from power surges. In addition to the design of the exterior of the aircraft, the lightning protection engineer must assure that no damaging surges or transients can be induced into the sensitive equipment inside of the aircraft. Lightning traveling on the exterior skin of an aircraft has the potential to induce transients into wires or equipment beneath the skin. These transients are called lightning indirect effects. Problems caused by indirect effects in cables and equipment are averted by careful shielding, grounding and the application of surge suppression devices when necessary. Every circuit and piece of equipment that is critical or essential to the safe flight and landing of an aircraft must be verified by the manufacturers to be protected against lightning in accordance with regulations of the FAA or a similar authority in the country of the aircraft's origin.

Aircraft made of primarily composite materials require designs for increased threats related to the larger resistance of the composite material. This requires careful examination of transport elements such as tubes and ducts that carry more current due to the aircraft skin resistance increase. Another constraint that may change aircraft designs may be the need for the aircraft to carry directed lightning currents that do not easily travel through the composite skins or composite structural components. This engineering challenge may result in addition of “metal” within the aircraft to carry lightning currents safely through the aircraft and out the extremities.

Another area of concern is the fuel system where even a tiny spark could be disastrous. Extreme precautions are taken to assure that lightning currents cannot cause sparks in any portion of an aircraft's fuel system or fuel vapor locations. Composite aircraft skin around the fuel tanks must be thick enough to withstand a burn through. All the structural joints and fasteners must be tightly designed to prevent sparks as lightning current passes from one section to another. Access doors, fuel filler caps and any vents must be designed and tested to withstand lightning. All the pipes and fuel lines that carry fuel to the engines, and the engines themselves, must be verified to be protected against lightning. In addition, new fuels that produce less explosive vapors are now widely used.

A radome is the nose cone of aircraft that contain radar and other flight instruments. The radome is an area of special concern for lightning protection engineers. In order to function, radar cannot be contained within a conductive enclosure. Protection is afforded by the application of lightning diverter strips along the outer surface of the radome. These strips can be solid metal bars or a series of closely spaced buttons of conductive material affixed to a plastic strip that is bonded adhesively to the radome. These strips are sized and spaced carefully according to simulated lightning attachment tests as shown in Figure 2-12 while also not significantly interfering with the radar. In many ways, diverter strips function like a lightning rod on a building.

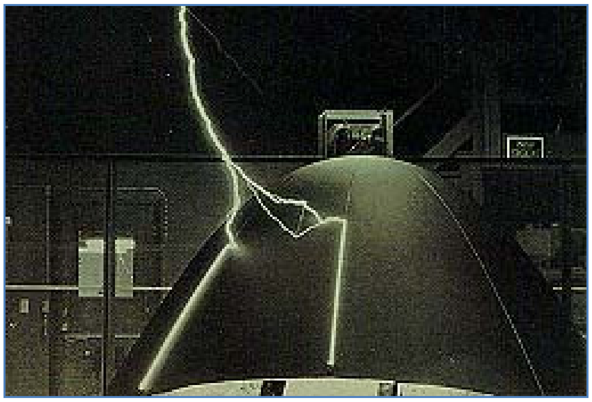


Figure 2-12 A typical lightning strike to radome protected by diverter strips

2.8.1 The Use of Qualification Testing in Determining Continued Airworthiness

The use of engineering data can be used to assist in determining the continued airworthiness of lightning/HIRF protection components such as critical wire bundle shielding. Integration of the continued airworthiness maintenance program development process and engineering test results will enhance aircraft operations. In the past, Aircraft compliance to FAR/JAR 25.1529 "Instructions for Continued Airworthiness" does not take full advantage of component qualification testing as a source of information used to establish a scheduled maintenance program. The premise of this paper is that some advantage can be gained through use of component qualification testing results to determine continued airworthiness maintenance requirements once equipment is in service.

2.8.1.1 Past Practices

Past techniques used to certify aircraft systems to specified lightning indirect effects may not include continued airworthiness compliance criteria [2.19] such as that required by FAR/JAR 25.1529. Without adequate continued airworthiness criteria established during the design phase, many aircraft system design firms have no choice but to establish continued airworthiness instructions after the design is complete. This approach to aircraft design is typical, where designs are developed through the design cycle and continued airworthiness evaluations are conducted later, even sometimes after the aircraft is certified and in operation. One early design criteria that can be addressed as part of the continued airworthiness might be a galvanic assessment of components that rely on conduction as a lightning protection measure. Galvanic assessments can be done as part of the continued airworthiness evaluation but may be initiated after design decisions are completed. For electromagnetic compatibility, qualification methods exist for establishment of transient level "margin" that accounts for uncertainties in verification methods [2.27]. Once aircraft installed system threat levels are determined – by test or analysis – they are extrapolated to external threat waveforms and levels. After this is completed, these threat levels are used to demonstrate "margin" [2.19]. Threat level margins and management of the design requirements are discussed in greater detail in paragraph 2.8.1.2. It is apparent within the industry that component design margins cannot be used to substantiate continued airworthiness however; use of test results may be insightful towards assessing performance in service.

2.8.1.2 Testing Requirements and Guidelines

To better understand the impact of establishing threat levels without consideration for continued airworthiness, this paper provides insights as to the practical application of the transient level margins for aircraft equipment. It needs to be clear that component qualification data cannot be used to predict continued airworthiness and the effect on EMC margins. Because it is rarely practical to perform full threat tests on fully configured aircraft, the key to successful protection will be the degree to which the system and subsystem tests simulate actual internal lightning environment in the complete aircraft with all its components interconnected and operational. These tests will depend in turn upon the accuracy of the airframe manufacturer's or system integrator's prediction of Transient Control Level (TCLs), the accuracy of Equipment Transient Design Level (ETDL) verification as tested by the system suppliers, and the sufficiency of the margins to account for any uncertainties in these conditions. In order to establish transient level design criteria for each system to be qualified, manufacturers will determine the lightning induced voltage and current waveforms and Actual Transient Levels (ATL) that can appear at the electrical/electronic equipment interfaces. In many cases, the induced transients will be defined in terms of the open circuit voltage and the short circuit current appearing at the wiring/equipment interfaces. The "v" and "i" will be related by the source impedances (i.e. loop impedance) of interconnecting wiring and there may be different levels determined for different circuit functions or operating voltages.

In addition, manufacturers need to establish Transient Control Levels (TCL) and Equipment Transient Design Levels (ETDL). The ETDLs represent the amplitude of voltage and/or current that the equipment is required to withstand or tolerate and remain operational (e.g. no damage or system, function upset). The TCLs, in turn, are set to equal to or higher that the maximum ATL. The difference between the ETDL and the TCL is the margin. The Equipment Transient Susceptibility Level (ETSL) is the amplitude of the voltage or current which, when applied to the equipment, will result in damage to components or upset such that the equipment can no longer perform its intended function. The relationship between ATLs, TCLs, ETDLs, and ESTLs is illustrated in Figure 2-13. The ETDL is usually stated in the specifications for the electrical/electronic equipment and constitutes a qualification test level for this equipment. Since ETDLs are typically represented by these standardized requirements, their use greatly simplifies compliance evaluation. Normally the TCLs and ETDLs will be established by the airframe manufacturer or system integrator, who will compare the penalties of vehicle or interconnecting wiring protection or equipment hardening to establish the most logical combination of TCLs and ETDLs. To verify compliance, testing engineers demonstrate that the ATLs appearing at the wiring/equipment interfaces do not exceed the established TCLs, and that the equipment can tolerate the ETDLs. Verification may be accomplished by demonstrating similarity with previously installed systems and/or equipment, by tests, or by analysis. Appropriate margins to account for uncertainties in the verification techniques may be required. More specifically, margins are incorporated to account for the uncertainties involved in the verification process. The magnitude of the margin is 6 db for critical systems with all others qualified to the ETDL. . The magnitude of the margin is also directly proportional to the degree that the system contributes to continued safe flight and landing as determined by the aircraft safety analysis. An acceptable margin is an essential element in the compliance process. Developmental test data may be used for certification when properly documented and coordinated with the responsible aviation certification authority [2.27].

For components being qualified, test set ups and applications of environmental threats are designed to evaluate any component effects observed during the qualification tests. These tests however, do not necessarily simulate multiple environmental threats simultaneously.

For determination of margin, the certification requirement for critical systems is 6db between ETDL and TCL Figure 2-13. Transient threat models such as the generalized model are typically established by Electromagnetic Effects (EME) engineers for a new aircraft development program as outlined in FAA AC 20-136 [2.21]. In the recent past, newer guidelines have been developed by committees under the Society of Automotive Engineers (SAE) and produced as Aerospace Recommended Practices (ARP). Since equipment is usually not tested to failure (destructive test), actual margin to failure (referred to as equipment transient susceptibility level) is often not known. Sometimes several tests of the same kind are needed to validate the TCL and margin. Continued airworthiness engineers do not use this data, as a clear correlation between the testing and the in-service performance is not predictable. Exposure intervals are dependent on being able to predict how aggressively a component will age. Thus far, the industry has not been able to reliably predict such trends at the component level without empirical data from in service experience. Historical “reliability” data may be used to provide guidance in cases where it exists. Without performance data from past aircraft operating experience or certification testing results, Lightning/HIRF maintenance program engineers must rely on past precedence of judgment from responsible design groups or conservative intervals that are led by the gathering of empirical data. Extension of these concerns by the FAA for lightning/HIRF protection performance over the life of the installation has driven Issue Papers requesting manufacturers to incorporate engineering validation programs to assure validate assumptions during the maintenance analysis process and potentially detect any early signs of lightning/HIRF protection degradation. Said another way, where the minimum scheduled maintenance program instructions may be inadequate to readily identify degradation beyond the established qualified margins (ETDL-TCL), the FAA has requested supplemental evaluation of the protection systems in service through an engineering validation program. Though this testing is valuable, the addition of in-service testing may extend from lack of confidence in the scheduled maintenance program development process (short of starting with extremely conservative intervals and then extending as operators provide feedback). After all, scheduled maintenance programs are developed to provide for continued safe and economic aircraft operation. For new equipment, with knowledge of the margin or test results along with expected aging of components over time (i.e. empirical in-service data), one can provide a very effective maintenance program with an engineering validation. Data can be supplied by suppliers or vendors with appropriate knowledge of in-service performance of the components key characteristics.

For this discussion, one must separate margins within the design transients and margins for component continued airworthiness. In comparing these concepts, an interesting problem emerges. Transient design margins do not model the aging associated with establishment of continued airworthiness margins. However, manufacturers can use margins from certification and design in support of MRB releases. With this approach in place, practically speaking, engineers use a tightly controlled process to determine which lightning/HIRF protection schemes to maintain and how often to impose maintenance action. In addition, in-service maintenance activities may test certification margins to ensure continued airworthiness is maintained. Creation of more effective maintenance programs can be enhanced if the component qualification data gathering process were to include continued airworthiness realities such as final installed environment as compared to the test environment results in the report. This is however not achievable and in order to establish a test interval in service, one has to be able to quantify failure trends from this data which has also not been achievable in the industry. Though some recent investigation identify simplistic comparisons between equipment qualification test data and aircraft measured induced responses to the effects of lightning as a thing of the past [2.23], current practices remain relatively unchanged for qualifying components to standards such as the DO-160E Section 22 [2.15] and MIL-STD-1757A [2.16]. More recent guidelines have been developed by SAE committees such as the SAE ARP 5412 [2.28] and SAE ARP 5416 [2.29]. Deterioration of protection over time still remains uncalculated and generates the need for the maintenance engineers to include in-service evaluations to assist in determining initial maintenance intervals for new protection systems, or substantiate the reliance on non-quantitative means for maintaining the aircraft.

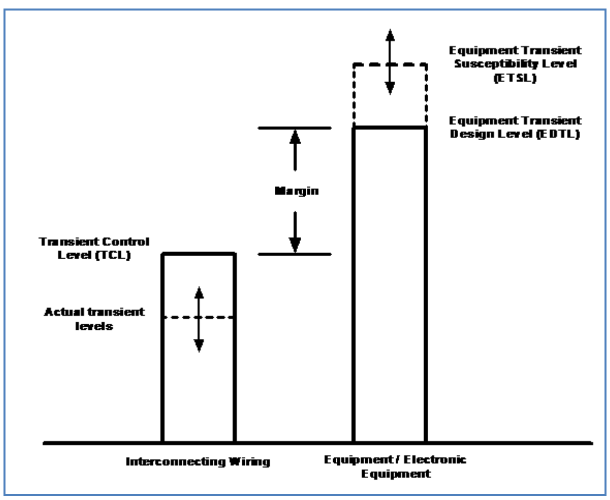


Figure 2-13 Relationships Between Transient Levels

2.8.1.3 Submitting Test Results

Modern lightning and HIRF qualification testing involves techniques for replicating electromagnetic effects including electromagnetic compatibility and lightning induced transients within singular environmental test arrangements. Test setups mimic aircraft installations but rarely replicate actual installation configurations and environment. Qualification testing on systems is not done on a full airplane level electromagnetic threat however, is accomplished with low or reduced level threat tests. These tests are performed on new hardware installations that are part of the system airplane qualifications. Because it is rarely practical to perform full threat tests on fully configured aircraft, the key for successful protection will be the degree to which the system and subsystem tests simulate actual internal lightning environment in the complete aircraft with all its components interconnected and operational [2.22]. For example, in-service "experience" cannot be replicated in a lab due to complications associated with application of simultaneous electromagnetic and environmental threats such as moisture, vibration, temperature, and pressure cycles applied to certified systems during operation on-wing. Other physical constraints also challenge testers to replicate actual installations such as the application of vibration, heat and moisture applied at the same time. A simple example of simulation challenges are cable length restrictions on the test unit due to lab size constraints. The RTCA DO-160 document [2.15] sets standards for emissions and susceptibility, lightning, electrostatic discharge (ESD), and other requirements such as vibration, temperature and humidity. These tests are typically run independent of each other on multiple units. Test results reflect only the test condition applied at the time of the test. Although the test procedures and methods are standardized by industry documents such as the RTCA DO-160 specification, suppliers have the responsibility for demonstrating that the performance of each Equipment Under Test (EUT) unit is tested and exercised with the hardware, interfaces, software and modes of operation representative of the test guidelines.

Qualification testing of components is limited to conducting separate environmental tests for each potential physical environmental threat. With this in mind, how can the testing ensure good performance once a lightning/HIRF protected component is deployed into service? Inability to simulate the airplane environment also contributes to the inability to predict degradation. In some cases an end of life values for components are validated for characteristics that provide for (resistance or transfer impedance) lightning protection. These values will help provide for consideration of component aging. In cases where these are included in the test results found in the qualification test report, one can consider the comments on the continued airworthiness of a tested component within the aging tests results. Revision to the design methodology might be considered to include criteria for establishing successful compliance with the continued airworthiness requirements that should be met during test. An example of how this can be accomplished is demonstrated in the practical application in 2.8.1.6.

2.8.1.4 The Qualification Test Report

Qualification test reports vary in the detail provided for specific testing. Typical information contained in qualification test reports includes:

1. Abstract
2. Scope
3. Conformity
4. Test Procedures and Setup
5. Conclusion

The key to providing successful test results are appropriate setup and simulation of the aircraft system under test. Conclusions of testing usually involve simple statements of pass or fail in tabular form along with individual testing results such as equipment measurements to demonstrate acceptable data points [2.24]. Incorporation of testing for the continued airworthiness is not part of current qualification processes. However, for new components, “end of life” values can be found as considerations during aging tests and may be embedded in the specification control documentation. Test report reviews sometimes include checks for significant technical contents similar to that provided below.

Test Report Content Checklist

1. Provide an adequate explanation of Equipment Under Test (EUT)
2. Provide an adequate description of equipment used and calibration dates
3. Supply a list of compliance, susceptibility, or emission outages per test mode
4. Ensure that the conclusion agrees with each test result
5. Ensure that the test is performed to a fully accepted test procedure
6. Provide list of any changes made to test procedure
8. Ensure that conformity is established
9. Ensure that where and when test was performed is in the report
10. Provide all photographs of each test setup in the report as well as any drawings
11. Provide data sheets stating equipment responses in each operating mode
12. Provide the level at which susceptibility no longer exists
13. Provide a list of all emission outages and plots
14. Provide any correction factors and bandwidths used in data analysis
15. Provide all susceptibility measures
16. Provide all emission measures

2.8.1.5 The Continued Airworthiness Evaluation

As we enter the age of advanced aircraft design, past methods for determining the continued airworthiness of lightning/HIRF protection are inadequate [2.18] to ensure robust and economical aircraft operations. As new methodologies are created [2.20] to handle evaluation of advanced lightning/HIRF protection systems, new ways to view qualification of lightning/HIRF protection components must be integrated into the design methodology. Use of the following mechanisms can assist in gaining better continued airworthiness programs:

1. In-service data collected from HIRF/lightning protection assurance testing
2. Qualification test data gathered during component qualification testing
3. Developmental test data captured during stress testing of new designs

As these processes are usually segregated, this paper suggests that the design methodology needs further consideration to include extension of data evaluations that include the continued airworthiness design criteria. Evaluations of the continued airworthiness can be gathered by way of test reports, in-service measurements, and developmental testing summaries. This integration of information must be applied within the constraints of practicality since work statements for such an effort can become quite large. This due to past practices within the industry of evaluating continued airworthiness after the design has matured. Engineers supporting this approach would be responsible for predicting aging trends that can conclude the robustness of the design based on a combination of the gathered test reports and data gathered in service.

With recent ATA Task Force development of a new methodology for determining scheduled maintenance of lightning/HIRF protection components [2.25], the use of performance data such as that gathered during qualification and developmental testing or in-service data gathered during maintenance checks has been accepted by the industry (Ref. Figure 2-14, Step 2 and Step 3) as a way to assist in determining appropriate scheduled maintenance requirements for lightning/HIRF protected equipment. This is a step in the right direction. In the absence of predictability revised processes for determining continued airworthiness and correlating efforts in testing to expected performance in service, a new design methodology evolves. Implementation of this approach requires early establishment of design requirements and a method for incorporating estimated robustness into the decision making for required scheduled maintenance. As this new methodology is implemented, analysis sheets can be generated that provide the maintenance engineer an assessment of the performance extrapolated for protection components under maintenance evaluation. This will require significant changes in both the maintenance evaluation process and in the design assessment of components.

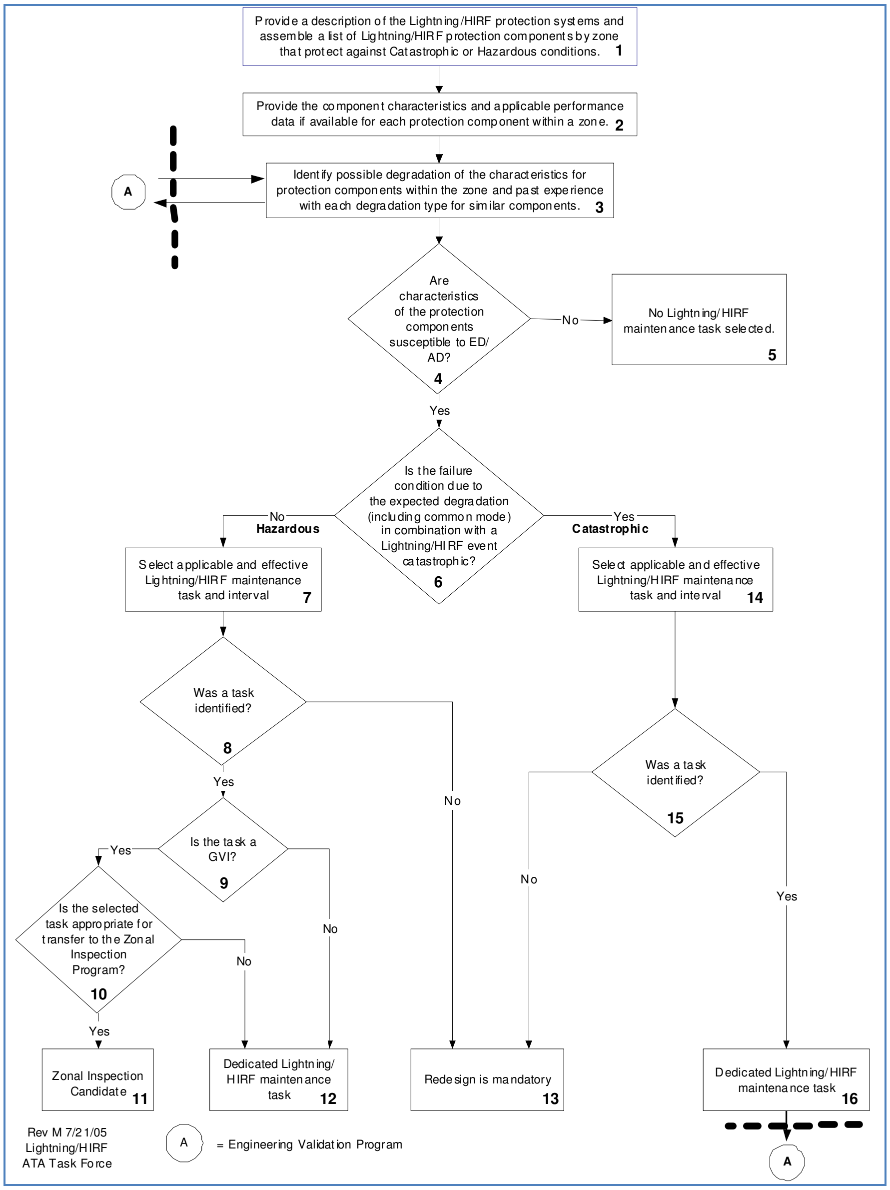


Figure 2-14 ATA Task Force Methodology for Lightning/HIRF MSG-3 Analysis

The new direction for the aviation industry begins the process of more closely integrating design methodologies with the continued airworthiness assessment process identified in AC 121-22A [2.25] that is required for aircraft type certification. While challenges using data such as this need further exploration and examination; how this new methodology will utilize test results is still under consideration. Implementation of the methodology requires manufacturers to design ways to include applicable accelerated aging testing information in the maintenance program analysis. This can be achieved through careful design of a maintenance program analysis technique that guides analysts using appropriate data when available. Specific implementation of the data may be achieved by providing engineering ratings of the data that is used to assess design robustness. Analysis sheets provide engineers a way to bring data together with reason and experience in determining continued airworthiness maintenance requirements.

2.8.1.6 Practical Application of Test Data

In order to model use of the test data coming from qualification testing, a practical application is created here to identify potential options for achieving the required engineering integration with maintenance programs analysis. Often, qualification reports simply provide the test results (data) and in some cases only provide data packages without specific interpretation [2.24] of things such as the transient margin described earlier in this paper. It is important to clarify that transient margins are not part of the component qualification and therefore do not reflect the ultimate application of the component. For this reason, transient margin is not correlated to the continued airworthiness assessment.

A high-level process flow for qualification testing (Figure 2-15) shows the focus of the test process as data collection and test arrangements (step 1, 2,and 3). Step 4 in the process is where potential engineering design methodology can be revised.

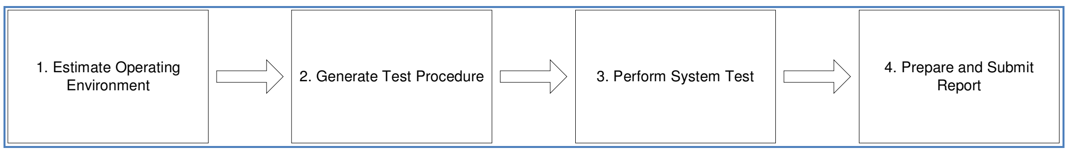


Figure 2-15 The Qualification Process

As it is the intent for the Equipment Under Test (EUT) arrangement and setup to simulate the airplane installation, the actual in-service environment presents a complex combination of effects that are most likely not achievable within the lab environment. Within the lab, simulation of interfacing equipment, loads, and interconnecting cable assemblies are typically quite readily achieved except during accelerated aging tests where they are typically not achieved. Often, experience shows that test arrangements can expose circuitry of EUT to inadequate levels of RF or transient energy, despite achieving the required test levels at the harness or equipment chassis [2.17]. The challenge for designers, testers, and qualification engineers is that the combination of environmental effects along with the simulated interconnections and electromagnetic environments simultaneously applied within a single test are not achievable since entire system installations are not subjected to accelerated aging tests. This challenge is a source for making predictability difficult. With a change in standards for developing data, the maintenance engineer can apply a more robust logic fed into the new methodology to determining long-term maintenance requirements. With processes in place to develop data that can be used in the continued airworthiness evaluation, continued airworthiness engineers can assimilate information into the MSG-3 analysis [2.20]. To implement this change, a means by which you can gather and develop data for continued airworthiness must be developed. After this is in place, two things can be done. 1) Addition of a paragraph to the Qualification Test Report that addresses the test engineers' assessments of the application of the EUT in service given the test results included in the report. 2) Incorporation of test report conclusions into analysis sheets for the required continued airworthiness MSG-3 analysis.

From this description, one sees both sides of the equation; the airworthiness process needed to develop a maintenance program contained in the FAA Advisory Circular AC 121-22A [2.26] and the qualification process outlined in DO-160E [2.15], supporting more robust recommendations that meet both safety and economic goals established within the design criteria.

2.8.1.7. Recommendations for Use of Test Data within a Design Methodology

Advantages of modifying the design methodology include:

- Improved technical evaluation of potential in-service degradation modes
- More effective maintenance programs
- Better performance of the lightning/HIRF protection components
- Improved operational economics

Final conclusions suggest that adoption of the continued airworthiness criteria within the engineering methodology outlined in this chapter will produce better performing designs by optimizing known performance information and in-service maintenance requirements. This expansion of scope should be well integrated and not negatively impact certification testing. It is expected that creation of the revised engineering process proposed above will more fully integrate continued airworthiness criteria into the design solutions at earlier stages in the design life cycle. This will be accomplished by modifying how tests are reported and how maintenance analysis is performed.

2.9 Conclusion of "What is Lightning?"

Based on the findings of research referenced in this chapter, the following is a list of the most important lightning strike characteristics impacting lightning protection continued airworthiness:

- Lightning attaches to aircraft most often in the outer extremities of the aircraft such as wing tip nose and rudder with fewer strikes occurring along the fuselage and wing root.
- Aircraft strikes occur most often during the aircraft climb
- Seventy percent of all lightning strikes occur during the presence of rain
- The probability of lightning strike to aircraft drops sharply above 20,000 feet
- There is a strong relationship between temperatures around 0 Degrees C and lightning strikes to aircraft
- Conditions that cause precipitation, may also cause electrical discharges
- Spring and Summer months are the most likely to create lightning attachments to aircraft
- Forty two percent of the strike incidents were reported where no thunderstorms had been reported by the pilots
- Lightning testing can be integrated into the protection design process

Lightning affects aircraft operations sometimes creating potential for a catastrophic outcome. For this reason, much has been accomplished in understanding natural lightning, its waveforms, attachment to aircraft and appropriate lab testing. Current FAA/EASA regulations address design considerations for lightning. Designers use simulation testing and idealized waveforms to establish the threat to safe flight and then implement protection within the aircraft design to minimize the effects of lightning. There is currently no design that will eliminate the attachment of lightning to aircraft. Because of this, lightning remains a major consideration in the certification of aircraft protection schemes. For the continued airworthiness of the lightning protection components, much is required to be established in the aviation industry to advance the new concepts in the maintenance and design methodologies affecting these critical protection systems. This includes development of new continued airworthiness criteria addressed by this research that advances concepts used within the design community today and theorizes a new methodology for lightning protection design continued airworthiness design.

Chapter 3 Lightning/HIRF Protection Continued Airworthiness Design Methodology

3.1 Reason for a New Methodology

The current methodology for development of Lightning/HIRF (L/HIRF) protection designs contained in Figure 3-1 can be improved to address continued airworthiness design decision functions. The steps included in Figure 3-1 do not include Step 4,5,7,8, and 9 since these steps are added as part of the improvements introduced later in this chapter. The revised methodology proposed in this body of work revises current aircraft design processes for implementation of protection designs with an augmentation of the design process to include continued airworthiness considerations. Supporting the adaptation of this new design methodology is the integration with the newly adopted MSG-3 maintenance program development methodology which will be discussed within this chapter. The proposed methodology also considers incorporation of MSG-3 as a step into the design process which creates a feedback loop for design revisions not previously performed for lightning protection continued airworthiness in the design of aircraft. As new composite aircraft structures drive new and more exotic bonding and ground designs, it is important to properly assess these new designs to ensure that the advantages of the new designs are not inappropriately burdened with maintenance and to ensure that the protection is available at all times. Without a methodology to address these design features early in the design process, new technology is exposed to potentially burdensome maintenance requirements in service. Application of this methodology can also benefit supplemental design revisions on older technology aircraft. Since the case studies performed in this PhD research utilized an aircraft designed in the late 1990's, evidence of the adaptability of the design methodology is provided later in the thesis.

3.2 Value of Proposed Methodology

Adoption of the proposed aircraft design methodology in Figure 3-2 is hypothesized to result in more efficient L/HIRF protection designs which require less scheduled maintenance and to improve redesign costs while optimizing design decisions during development of a new transport category aircraft. Creation of a component assessment sheet including detailed assessments of engineering robustness within installed environments using test data, and a galvanic junction rating scale is expected to reduce demands for more maintenance tasks. This methodology is also proposed to result in valuable design improvements, such as: improved bonding installations, improved material and fastener selections, electrically robust structural attach points, and more maintainable ground strap routing. If properly applied, the methodology will also increase visibility of continued airworthiness within the design process and drive bonding design performance issues required for the life of the aircraft that may, prior to incorporation of this methodology, have been taken for granted and subsequently, not implemented.

In recent evaluations of maintenance programs, it has been noted that a new MSG-3 analysis methodology was necessary to improve the decision making logic. The value of the design methodology captured within this thesis goes beyond theoretical as this methodology is intended to provide better connection to the initial scheduled maintenance program development process.

Lightning protection in an aircraft zone may contain different types of protection which requires different methods of inspection. As discussed within this thesis, the minimum initial scheduled maintenance inspection requirements, which are used as the basis for the operator's maintenance program, are developed through the MSG-3 analysis process and provided in the manufacturers Maintenance Review Board Report (MRBR) approved by the regulatory authorities. [3.1]
The MRB procedures are developed according to the following documents:

1. JAA Administrative & Guidance Material (AGM) Section Two: Maintenance Part Two: Procedures Chapter 16: Procedure for Maintenance Review Board [3.2]
2. FAA Advisory Circular 121-22A: Maintenance Review Board Procedures [3.3]
3. ATA MSG3-rev 2002.1

Within the MSG-3 analysis process, a specific working group is in charge of making analysis of lightning protection designs. The type of data which are necessary to follow MSG-3 procedures to fulfill the MSG-3 method requirement specifically applicable to lightning protections is also in-part, the data necessary to develop the design of lightning protection components presented in this body of work. The type of analysis which is conducted for providing the information required by the MSG3 methodology with the surveillance methods related to each protection type followed by the validation of these surveillance methods forms a new basis for lightning protection maintenance program development. Thus, the design methodology proposed by this body of work is a logical next step in the development of new methodologies associated with more complex aircraft designs.
Each step in the methodology is a process for which more detailed discussions can be provided. The purpose of the methodology is not to create more detailed discussions of these individual processes. In the descriptions below, the minimum amount of discussion is provided to gain understanding of the purpose of each process in order to understand the purpose of the proposed methodology.

3.3 The Current Design Methodology for Lightning Protection Development

Current design practices include steps that address the lightning and HIRF threats for to ensure the continued safe flight and landing of the aircraft after a lightning or

HIRF event. This methodology is driven by electromagnetic requirements that are imposed on the design process. Electromagnetic design engineers are engaged during the aircraft development to ensure that other design groups are aware of critical design criteria when making design implementation decisions. Test data plays a role in determining if certain design implementations meet the requirements. For instance, a fastener may be required to carry current during a lightning strike event without causing a spark within an ignition zone. Engineering testing may be required to assess different alternatives to the fastener installation and location. The use of sealant may also be tested for its ability to contain a spark during a lightning strike. The typical design considerations focus on solving problems such as the following:

a) **Identification of Lightning/HIRF environmental threat.** This is normally accomplished by use of common industry guidance found in design text books. Continued availability of lightning protection over the life of an aircraft can be affected by environmental conditions such as moisture, vibration and temperature or each lightning protection component installation. These conditions need to be evaluated for issues that arise such as loose fasteners, gaps in bonding paths, and corrosion or heat damage.
b) **Aircraft lightning zoning**. During the design of an aircraft, zones are determined by models used by designers that take into account the geometry of the aircraft and assert areas on the aircraft that have the highest lightning strike threats on down to the least threatening lightning strike. An example is found in chapter 2. This zone exercise would not normally evaluate the installed lightning protection within the lightning zone to determine the significance of the zone. Threats for composite aircraft can be as much as 1000 times greater than threats for aluminum aircraft. For composite aircraft the zone definitions may be similar than non-composite aircraft, however, the amount of aircraft system standoff voltage may be increased in order to further protect the aircraft from these higher voltages.
c) **Classification of Lightning/HIRF protection systems criticality associated with the continued safe flight and landing of the aircraft.** As aircraft are designed, systems failures are classified as critical or essential to the safety of the continued operation of the aircraft. Loss of the protection in combination with a lightning/HIRF event is used as a way to determine certain protection criticality. In the past, this involved simply listing all the Level A (Critical) and Level B (Essential) equipment on the aircraft. Today, this terminology has been eliminated as a harmonization of the regulatory definitions of catastrophic, hazardous, and hazardous-major are now in place. Generalization of this definition called out by the International MRB policy Board in February of 2007, have allowed for broader inclusion of structural and mechanical system components into the list of protection systems that require evaluation for continued airworthiness. Current practices for lightning protection classification integrate the systems safety analysis classifications with the EMC function Design Assurance Level classifications.
d) **Bonding and Grounding techniques that meet a minimum joint resistance throughout the wire/loom designs.** This also includes wire terminations for electrical bonds. The importance of metal compatibility and sealant applications is applied by design teams. For composite materials, there may be more

challenging criteria to address associated with driving current into composite material and ensuring sparks are not encouraged by the larger voltages generated from the less conductive materials.

The current design methodology referenced in Figure 3-1 shows the design processes that are contained in current practices. Within the engineering analysis and design development portion of the figure, design activities are iterative. These iterative steps affect the processes of establishing design requirements. Some of the design requirements are revised after certain tests are completed. Criticality of the equipment can also change as the design matures and test results are evaluated. This approach to aircraft lightning protection design is focused on the development of systems and components that meet the protection requirements. Practical implementations of the designs that meet these requirements are not required to be subjected to further analysis for long term maintenance of the initial design. The focus at the time of the design is to meet requirements for successful certification of the aircraft. The following is a description of each design process included in Figure 3-1 and the association of each design step to the aircraft final definition.

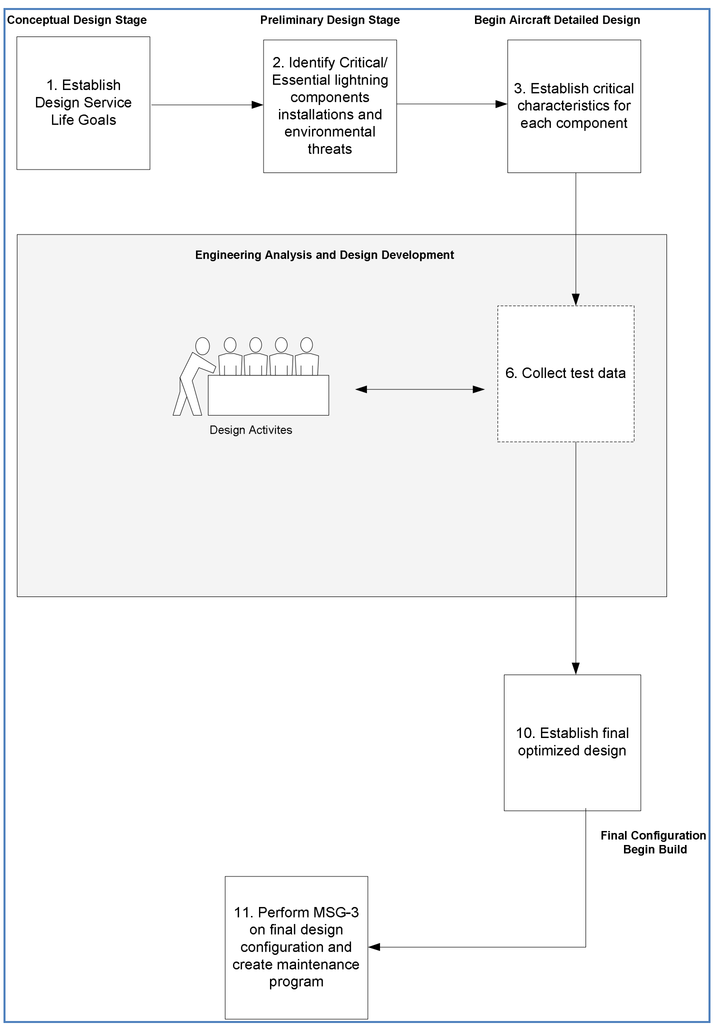


Figure 3-1 Process for Lightning Protection Continued Airworthiness MSG-3 Analysis

Step 1 - Establish Design Service Life Goals

During the conceptual design phase of the aircraft development project, the design goals are defined as design requirements and objectives. At this design stage, engineering designers input design service goals for aircraft continued airworthiness. Outside this design function is a parallel study of protection systems design performance conducted through feedback from aircraft operators. This process is better understood by service engineering personnel that may not be an integral part of the new aircraft design, though more recent design programs have included this input with various approaches. Service and support engineering can be very helpful towards creating the needed designs service goals since these engineers typically maintain expertise in aircraft operations support. The design service life objectives development process uses inputs from service experience but may not be an integrated part of the design team function depicted in Figure 3-1 as a group of engineers labeled “Design Activities”. This design guidance for the Service Life Goals usually incorporates improvements from past aircraft products that reduce maintenance and improve availability, thus increasing the aircraft ability to generate revenue. Typically, this guide establishes:

a. Number of years’ service life
b. Scheduled maintenance goals (maintenance intervals and time out of service for maintenance and repairs)
c. Accessibility and maintainability

These “Design Service Life” goals are input to aircraft designers as part of the initial conceptual stages of the aircraft design process. This process includes aircraft mission goals such as 20 years of service, 60,000 flight hours and 40,000 flight cycles. During this phase of an aircraft design program, materials are selected, physical geometry is determined, and performance is continuously calculated to guide multiple engineering disciplines to a logical final configuration. The new methodology presented in this work suggests that lightning protection design be part of the earliest stages of the design process to ensure that the most optimal lightning protection design is defined within the boundaries of the established design goals. For composite aircraft this will include significant design decision inputs in the area of composite structures protection such as imbedded foils and mesh application decisions. Areas that have the highest probability of a lightning strike and where the greatest electrical current may be transferred to the aircraft, called Lightning Zone 1, should be examined for protection design optimizations at this stage in the aircraft design. As design decisions become firm, lightning protection of composite structure must ensure that any potential maintenance action to maintain the continued airworthiness of the aircraft is achievable within the aircraft operator environment. Designs where continued airworthiness actions are not possible should be revised, lest maintenance is determined necessary later in the development program (after Step 11 in the methodology) and more severe consequences are realized such as exotic testing or protection component replacements (Hard Time) are imposed to ensure that the continued airworthiness is maintained. Part of this input to the methodology includes awareness of accessibility to protection devices and components. It is often the case that poor accessibility leads to more intense ground time and lost revenues. One very important aspect of Step 1 is to remember to include composite structure lightning protection in the maintainability study that marks this stage of most aircraft design processes. It is imperative at this stage of the design that the aircraft manufacturer involves engineers with service experience to add another level of reasoning to the early design implementation decisions.

Step 2 - Identify Critical/Essential lightning components/installation and environmental threats

During the preliminary design phase, aircraft lightning protection is determined with the specific outcome to provide adequate conductive paths so that lightning currents do not create a hazardous or catastrophic condition. It is important to note early in a design program that conductive paths are provided by systems control wiring, structure and transport elements such as hydraulic and fuel system tubes. For this reason, designers are careful to ensure that adequate current paths are provided given the lightning current model created by the lightning zone determination process and the associated calculated lightning currents. Suppression of dangerous surges may be necessary through use of suppression devices or adequate current paths provided by bonding and grounding techniques. Engineering efforts are guided by experience, industry standards and regulatory guidance.

Some of the sources for regulatory guidance associated with lightning threats are:

a. Systems safety analysis (Catastrophic and Hazardous)
b. Structural elements direct effects (FAR 25.581)
c. Ignition prevention protection (FAR 25.981)
d. System upset due to Lightning/HIRF (FAR 25.1316)

Identification of L/HIRF protection components is made during the preliminary design phase of the aircraft development program after the lightning current threats are defined. Significant lightning protection components are those installations and devices whose failure can result in a potential catastrophic or hazardous condition [3.4]. Once a protection scheme is established during the aircraft preliminary design and is determined to provide protection against the potential for a catastrophic or hazardous condition, documentation of the component should be established and in particular, the installed environment should be identified.

Component	Condition	Environment	Design Threat
Hydraulic transport element protector	Catastrophic	Moisture	Corrosion of installation fittings
Current path conducting joint in aircraft structure	Catastrophic	Temperature and Vibrations	Looseness of joint due to expansions and vibrations
Wing skin conducting path	Catastrophic	Low and high frequency vibrations from wing deflection and engines mounted on underside of wing	Loss of conducting path continuity to ground plane

Table 3-1 Identification of Lightning/HIRF Significant Protective Components

A matrix such as the example in Table 3-1 below might be used for this engineering analysis to determine specific requirements for installation and evaluation of the components. To meet the requirements for continued airworthiness, these components and associated environmental threats should be evaluated during the preliminary design stage of the aircraft development program. The reason that it is important to examine the designs at this stage for continued airworthiness performance is if changes proposed due to the continued airworthiness evaluation may be more easily implemented at this preliminary design stage. At this stage, the list of components such as the example shown in Table 3-1 can be gathered by and engineering integrator and continuously evaluated for impact as more specific design decisions are made heading towards the detailed design stage.

As the design of the aircraft matures, the list of significant protection items will stabilize. This list may be managed by an electromagnetic continued airworthiness engineer and considered by those engineering departments responsible for the protection design implementation. Formal identification and documentation of the protection components will ensure smooth transmission of the significant components to the MSG-3 analysis. However, as depicted in the Figure 3-1, the MSG-3 analysis is not included within the Engineering Analysis and Design Development process where design activities are conducted. This arrangement may generate unwanted maintenance since MSG-3 analysis will occur later in the design process when design changes become more costly. As the configuration of these protection designs are firmed up, consideration for the continued airworthiness of the installations can be performed by the identification of critical characteristics and environmental threats that may be present as the aircraft enters its service life. If this assessment concludes that the subsequent MSG-3 analysis will find required maintenance for the design developed in the preliminary design phase, then feedback through the design activities process would be beneficial at that point. With the current design process, this feedback is not conducted formally however; clever designers may realize the impacts of certain decisions and contact appropriate counterparts to affect beneficial changes.

Step 3 - Establish critical characteristics of each component

Critical characteristics are those design features that enable a component to perform its lightning protection function. Some characteristics might be galvanic protection coatings on lightning shields, sealants used to avoid moisture ingress, and other installation details that ensure a component can perform its lightning protection function without degrading to a point where the component is no longer effective. An Air Transport Association (ATA) Task Force was conducted from 2005 to 2007 with the purpose to address improvements needed to the Lightning/HIRF MSG-3 Methodology. In the MSG-3 document rewrite, the newly adopted industry definitions of a component and component characteristics [3.5] are as follows:

Terms:

> <u>L/HIRF Protection Systems</u> are comprised of components that avoid, eliminate, or reduce the consequences of an L/HIRF event.

L/HIRF Protection Component is any self-contained part, combination of parts, subassemblies, units, or structures that perform a distinctive function necessary to provide L/HIRF protection.
Characteristics are those properties of L/HIRF protection components that are necessary to perform their intended L/HIRF protection function(s).

Key to assessing the continued airworthiness of a particular design is the identification of component characteristics. These characteristics may be susceptible to degradation from environmental factors over time.
Properties that may degrade over time can include:

a. Materials and galvanic junctions. This can include both conductive and non-conductive materials. Designs that require the interface of incompatible materials such as stainless steel fasteners through carbon composite structure may require mitigation by a non-conductive material. If conduction of the joint is needed to reduce the threat of damage due to lightning, then more careful examination of the design is needed.
b. Bond path components. In some cases, electrical bond paths may be created by incorporating bond wires from a component to the aircraft electrical ground. It is important to ensure that the bond wire fasteners and material are free from potential corrosion or if this is not possible, that the potential for corrosion is mitigated by appropriate installation techniques. Bond paths can also be secured through the use of fayed surface bonds produced with use of high torque fasteners. Though the fasteners may not always be in the bond path, it is still important to evaluate the continued airworthiness of the fayed surface is cases where the fasteners may break or loosen and subsequently cause the interface to become a high resistance joint.
c. Installation design materials and hardware in specific locations. An installation of a component can be quite eloquent. Bond paths, isolation and insulation may all work together to provide the appropriate lightning transient mitigation against damage to equipment from the lightning strike. Details of the installations such as brackets, structural mounting and isolating materials require identification for a continued airworthiness assessment to ensure a long term availability of the component protection function. Consideration of whether a component is installed inside or outside of the pressure vessel provides insight to the continued airworthiness challenge for that particular component.
d. Wire looms and hardware. Connectors and associated electromagnetic shielding require specific material choices and secure installation solutions. Disconnect brackets for continuance of wire bundles through aircraft structural production breaks are also equally important to include in the characteristics evaluation.

Step 6 – Collect test data

Step six in Figure 3-1 is marked with a dashed line around the box that represents a current data collection process that is slightly different than the one that is proposed by step six in the methodology central to these studies found in Figure 3-2. As designs are developed, past design approaches are heavily leveraged into new aircraft engineering choices to reduce costs and create fewer new spare part requirements. In the case of lightning protection, most designs are not active systems that can provide reliability data based on system upsets recorded while the aircraft is operating. In this case, the use of past system performance records is not effective to determine if a bond jumper or lightning protective strip on an aircraft wing tip has performed well over the years of operation. In this case, the current lightning protection data collection in step six may come from examination of pilot reports of system upsets after a lightning strike or accidental findings of damage caused by a lightning strike that is found in the post lightning strike aircraft walk around inspection. Some of this data is available but much of it is not. It is difficult to correlate lightning strike events to aircraft system upsets especially since these correlations would be best performed at the airline with complete access to both the pilot reports and the aircraft itself. An aircraft manufacturer often does not have such access and finds it difficult to collect this kind of evidence correlating performance of the components over time to the initial expected design standards designed into lightning strike protection components. For this step, lab results may be used during the early design phase of the aircraft development. These lab tests are typically not performed to prove that the design will meet continued airworthiness requirements; rather they are typically conducted when a new design is desired such as revised fasteners, new materials or new structural components that have not been used in conjunction with the proposed installed components.

Step 10 – Establish final optimized design

In the current view of the design development captured in Figure 3-1 the step six feeds directly into step ten. This is because the steps between step six and step ten are added steps found in Figure 3-2 which are part of the revised methodology that do not exist in the current representation of the design process depicted in Figure 3.1 above. As the design alternatives are reduced to an optimum implementation, final design decision for L/HIRF protection components are established. Once these designs are completed within the process outlined in previous steps, final configuration is established and full scale production of the first article can begin. At this point, final conclusions regarding the expected in-service performance and assumptions used in making the design decisions are recorded. Final design characteristics, test performance and expected performance while deployed in service can be included as additional detail in the continued airworthiness document mentioned in Step six of the new methodology detailed in Figure 3-2. This documentation of design requirements and test data collection will be important as a communication tool between design and continued airworthiness engineers during the early phases of the aircraft development program. Some of the key expected activities associated with step ten include:

a. Stabilize configuration
b. Summarize key required design features
c. Revise characteristics for final release
d. Document expected service performance
e. Complete tests for determining effective design configurations

At this point in the design process, the aircraft can begin initial construction. Drawings, diagrams, and specifications are sufficiently mature in this phase of the aircraft development program to begin production.

Step 11 – Perform MSG-3 on the final design configuration
In order for the maintenance program to be created in the current development method, sufficient design completion is required. At this point in the development program, final configuration is fixed and aircraft production begins. Concurrent with these activities is the initiation of the MSG-3 process. For MSG-3 analysis to be effective, sufficient design details are required. As such, this is an appropriate place in time to conduct the MSG-3 analysis. If an MSG-3 analysis determines a design is not robust enough to last the life of the aircraft, maintenance will be applied to the design for the life of the aircraft. At this point in the design phase, revising the design is impossible without a negative impact to cost and schedule. At this point, the opportunity to revise designs has past. If diligence is used in the design decisions made earlier in the program, MSG-3 analysis should expect to find excellent performing designs that require little maintenance. In Figure 3-1, step eleven is the final step of the continued airworthiness design development. Within step eleven the process is initiated to create a maintenance program for the aircraft. In the new methodology this step remains at the end of the design process but the expected outcome is different and is explored in greater detail below as part of the Figure 3-2 methodology discussion. With this process reflecting current practices for design development two significant outcomes will result in less desirable outcomes:

1. Additional Maintenance - Without the ability to input continued airworthiness criteria within the current design development flow shown in Figure 3-1, those lightning protection systems that protect critical and essential aircraft functions are more likely to require additional maintenance to ensure continued operational effectiveness. An example may be a fastener hardware combination that meets the required resistance values at initial installation, and has passed the 500 hour certification tests without significant degradation of the resistance. This component may be installed in the aircraft wheel-well where additional threats exist over a much longer period of time could prove to have a worse effect on the long-term provisions for low resistance within the hardware interfacing joints.
2. Lower performing lightning protection designs – Many designs for lightning protection are not subjected to a design revision study if the initial testing provides good results. If the testing that was competed was to meet certification requirements, the test may not have explored environmental threats that more closely represent the aircraft condition such as air pressure cycling. Air pressure cycling can have an effect on filet seals that are not installed well. For instance, a filet seal that has an unexpected gap or pin hole in the sealant may actually draw moisture in and out of the gap due to pressure cycles as the aircraft moves through changing altitudes. For this reason, filet seals may not be the best alternative outside the pressure vessel. In a certification test, a filet seal may perform very well in the 500 hours salt spray exposure to complete the moisture testing. A gap in the sealant may not generate any problem in allowing moisture to enter into the hardware joints.

3.4 Proposed Methodology

To understand the methodology proposed by the author, each step within the new design methodology is described below. As the first steps in the process are very similar to steps already performed by aircraft designers, a note is made in those step explanations to direct the reader to the current methodology included in Figure 3-1 above. The key to successful deployment of this methodology is the provision for an integration of engineering talent within the aircraft design community. This integrated design community will also include a function that will act as a “gatekeeper” of issues related to continued airworthiness. For lightning protection, this may be a new concept in aircraft design programs since the continued airworthiness of lightning protection is relatively new criteria imposed by regulatory agencies in the wake of more integrated aircraft systems that can be impacted in a common way by a single lightning strike. Along with this integration of talent is the integration of information. An example of this information integration may be the use of in-service performance data as part of the data collection used to assist in design decision making. In service performance data for lightning protection is less prevalent and does not have the deep information-rich characteristics as does many of the other more common airplane functional designs. The first step in any development program is to determine the goals that will drive the solutions.

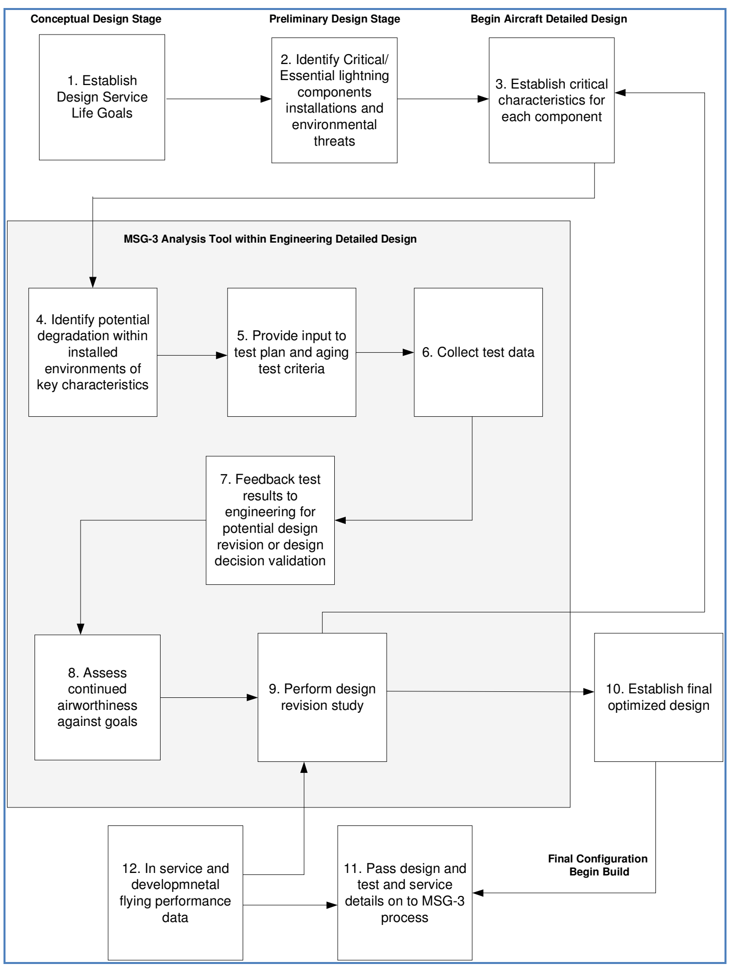


Figure 3-2 Design Methodology for Lightning Protection Continued Airworthiness and MSG-3 Analysis

Step 1 of New Methodology - Establish Design Service Life Goals

Definition of this step is included in Section 3.3 of this chapter. The step description and expectations are similar for the new methodology. Consideration of the long term availability of lightning protection may be a new design service life goal that was not included in past aircraft design programs at this stage.

Step 2 of New Methodology - Identify Critical/Essential lightning components/installation and environmental threats

Definition of this step is included in Section 3.3 of this chapter. The step description and expectations are similar for the new methodology. Consideration of the long term availability of lightning protection may be a new additional consideration during selection of critical and essential lightning components installations and environmental threats. It is important for an aircraft development program at this stage to determine the way forward for certification. In this stage, lightning protection continued airworthiness may require re-assessment of the choices made for the lightning protection components that are required.

Step 3 of New Methodology - Establish critical characteristics of each component

In the currently proposed design method shown in Figure 3-1, critical component characteristics are determined at the beginning of the detailed design phase of the aircraft design process in the same way proposed in Figure 3-2 with differences to the inputs and outputs. The proposed new methodology has the establishment of critical characteristics of each component in the same step three of the methodology in Figure 3-1 above however have different interfaces that improve the design methodology. With the step three timing being conducted at the beginning of the detailed design phase there may result a negative impact on the outcome of the design and generate more maintenance as described in step eleven within section 3.3 above if design characteristics are chosen to meet impedance requirements and not to include continued airworthiness criteria as shown in the interfaces to step three that were not part of the previous design process. One example is the use of tin-plated copper shields used in looms to protect against lightning. These shields may provide excellent impedance performance and may have been qualified to meet moisture exposure with a 500 hour salt spray. However, use of service experience shows that these tin plated shields do not perform well outside the pressure vessel. In this case, the effect of this information is brought into step three by the feedback loop from step nine where a design revision studies are performed to determine if the design should be chosen as the final optimized solution. The service experience would be included in the design evaluation. This feedback is a major improvement over the past methodology described in Figure 3-1 where final characteristics are declared as a matter of fact at the beginning of the detailed design phase based on the ability of the component to pass certification without detailed consideration of the continued airworthiness aspect of the characteristics within the installed environment. The next major improvement proposed by this new methodology is the revision of practices to pass the established critical characteristics to a new design process listed as step four that will evaluate the characteristics for potential degradation within the installed environment. This evaluation is new to the design methodology used in the past explained in step four below.

Step 4 of New Methodology - Identify potential for degradation of characteristics within installed environment

Once the key characteristics are established for lightning protection components, a dedicated effort to identify all possible degradations imposed by the environment over time is necessary. Degradations are most probably due to environments in which the protection is installed and the ability of the design to eliminate degradation potential through good design techniques. Some of the leading degradation modes are listed below.

a. **Galvanic junctions (corrosion).** For those Lightning/HIRF protection components that can corrode when interfaced directly, note should be taken with regards to the potential degradation given the installation location and materials corrosion mitigation design.
b. **Fatigue.** Loss of conductive path can be a degradation mode for Lightning/HIRF components if anticipated vibrations or other environmental conditions cause material fatigue that leads to loss of material continuity or interfacing.
c. **Mechanical malfunction or wear.** Duty cycles of aircraft equipment and structure should be identified where appropriate as potential degradations of conductive paths. An example of this might be the extension and retraction of control surfaces that contain specific bond path designs such as bond wires or specific structural current path designs through structural components.
d. **Heat damage.** Heat can cause negative effects on sealants and isolation devices such as gaskets. Degradation modes contributed to heat should be considered when developing the degradation mode identification.
e. **Extreme temperature cycles.** Extreme temperature cycles can cause lightning protection components to expand and contract. Use of different materials in bonding and grounding designs, expansion and contraction can cause interfaces to loosen or loose the required intimate contact.
f. **Delamination or disbonding.** Some composite structures provide lightning protection by use of Expanded Aluminum Foils (EAF) or Bonded Aluminum Foils. Water ingress into composite honeycomb structure can freeze and cause damage to the underlying structural integrity of the composite panel. This can also lead to degradation of the protection provided by the imbedded metals as moisture introduces corrosion potential for the embedded metal.

To capture the specific degradation modes and impact of the environment on the protection designs, a table is included in an assessment sheet that is used to grade the effectiveness of the designs when exposed to longer term elements present within the installed zone. The combination of these threats is also important to consider. An example of a combination of threats that impact a protection scheme is one where nickel plated aluminum connectors are deployed in moisture prone areas that experience sever temperature cycles. These connectors perform very well in moist areas where temperature cycles are not extreme. However, if temperature cycling and moisture are present at the same time, the performance is degraded considerably. This is because the aluminum coating on the connector surface and the aluminum material expand at different rates when exposed to extreme temperature cycles. With these different expansion rates, the aluminum finish sustains small fissure cracks that expose small amounts of the underlying aluminum. When exposed to moisture, this combination of dissimilar materials causes aggressive corrosion on the exterior of the connector and ultimately degrade the performance of the connector exterior as a good bond path for lightning current to travel.

Step 5 of New Methodology - Provide input to test plan and aging test criteria
With installed environment knowledge, the design features and the potential degradations modes, one can make valuable input into the lightning protection testing plans. Use of design influencing mechanisms can assist in gaining better continued airworthiness programs within the Engineering Detailed Design phase [3.6]. The tests that may be influenced through use of this methodology are:
1. Qualification test data gathered during component qualification testing
2. Developmental test data captured during stress testing of new designs

As electromagnetic environments are defined by aircraft development engineers and qualification test requirements are established, consideration for the nature of the installed environment can provide further insight to the continued airworthiness of components under test. Though the challenge with qualification testing is that true degradation profiles cannot be reproduced in the laboratory environment, developmental testing of components can provide some indication of a components ability to continue functioning under extreme environments.
Inputs to the test plans should include establishing the aging test criteria in step five provided in the following list:

A. **Design service life objective comparison to test profile simulations.** This information can determine how close to design life the different tests are conducted.
    a. Flight Cycles
    b. Flight hours
    c. Years
B. **Installed location.** With this information one can estimate the severity of the environmental exposure anticipated during aircraft operations.
    a. Inside Pressure Vessel
    b. Outside Pressure Vessel Protected
    c. Outside Pressure Vessel Exposed
C. **Test to failure required – Yes or No.** With this information one can gain additional information to derive the end of life values for predicable degradation. For unpredictable degradation, testing to failure may be the only choice as the gain from testing to failure will not be applicable in normal operations. In order to determine the value of testing to failure a test engineering may consider use of test scenarios through:
    a. Information gathering regarding probable aging profile based on application of component within its installed configuration
    b. Information gathering regarding maximum failed condition values and appropriate margins
D. **Aircraft worst case environment comparison to test standard.** With this information one can conclude the potential operating margin between the worst case operating environments and the testing conditions established for laboratory simulations. Though these may not be directly comparable, it may be

wise to re-examine the design if the operational margins run too close to those simulated environments.

a. Temperature
b. Moisture
c. Chemical threats
d. Vibration

E. **Galvanic junction assessments.** With this information on intentional and non-intentional galvanic junctions like those that might be used in aircraft component grounding to structure, one can ensure that the testing would provide resistance increases throughout the test. Large resistance changes due to aging of component parts are often a threat to continued availability of adequate lightning protection. Mitigations against corrosion of galvanic junctions such as sealants should also be included in the testing if possible. This will provide the continued airworthiness engineer with a better idea of the design robustness when subjected to the different tests.

F. **Test Setup Criteria.** When comparing the aircraft system installations to laboratory setup it is often impractical to simulate the exact configuration of the aircraft installation and provide the exact combination of threats over a large period of time. Because the location of the installation, geometry, and combined environmental threats may together establish a unique challenge for test engineers, the test findings must be scrutinized closely. Making the mistake of accepting laboratory results without consideration for the test set-up simulation might result in erroneous continued airworthiness conclusions

G. **Effects of fatigue on electrical properties.** Flight cycles and vibrations can have an effect on the longevity of the electrical connection. Some examples might include bond straps on control surfaces that fatigue to failure in service, broken or loose connector back shells that interrupt adequate bond path, and hydraulic line clamps that are conductive and assist with transferring large lightning currents during a lightning strike event. Stress and fatigues tests effect on electrical conduction may not normally be part of the test plan. Inputs from the continued airworthiness engineer can ensure that the fatigue tests include follow-up measurement of the conductive joints.

Step 6 of New Methodology - Collect test data

Step six is slightly revised in the proposed methodology and depicted in Figure 3-2 as a solid line around the box. To support this proposed new methodology, Step six recommends that a survey is devised to collect the data that reflects the interests of the inputs made in Step five which investigate the performance of components both based on certification tests and based on subsequent tests. In the development of a new aircraft design, the primary focus of testing is certification of the aircraft type design. It is up to the continued airworthiness engineer to establish the vehicle in which the data will be collected for continued airworthiness design inputs. A continued airworthiness document may be the best way for an aircraft OEM to centralize this information and refer specific information into the MSG-3 process at a later time. Certain hardware should have historical information regarding its ability to maintain its function over time. One could investigate these components by testing the hardware on retired aircraft or performing a survey of these components at airline sites. Additional information should be available within the product support division of the aircraft manufacturer. Since much of this information may be collected as part of service investigations for system failures on aircraft in operation, the details required for this new methodology may not be gathered as part of the investigations. Data collection is an important factor in successful use of this methodology. Many aircraft designed after 1995 have an FAA requirement to perform in service testing of lightning protection. Results of this testing is a possible source for the needed data and should be aligned with the new methodology.

Step 7 of New Methodology - Supply test results to engineering staff for potential design revision or design validation

Once the test results have been assessed for continued airworthiness, the engineer concerned with the continued airworthiness of the design will provide guidance regarding the test results associated with the test itself and aging simulation discussed in Step 5 of this new methodology. It is well known to some test engineers that components pass qualification tests in the laboratory and fail to perform in service for the life of the aircraft. It may be beneficial at this stage in Step 7 to take developmental testing results into account as well if they are available. This developmental testing usually explores breaking points in the design and abuse characteristics beyond that which is required for qualification testing though developmental testing may not be as controlled as qualification testing. A combination of evaluations associated with these two test results is proposed to draw a better conclusion as to whether the design will meet the design goals set earlier in this methodology. Continued airworthiness engineers will provide assessments of the expected performance of components based on experience with similar designs or in-service testing performed by airline maintenance crews. Other sources of data may be exploratory testing where aircraft that are no longer in service may be destructively tested to determine the amount of degradation in a particular bond scheme. Aircraft manufacturers may be well served to create databases for L/HIRF protection component performance data and utilize this data to affect design development and improvement. Though it is rare to see these lightning protection components within the reliability databases where system performance is retained, this may also be an opportunity to improve data collection and utilization. Gaps that may exist between service engineering knowledge and system designers can be bridged if data is collected and retained for lightning protection. In cases where the test results show serious lack of robustness in the design to continue good performance in the installed environment, a request for an engineering trade study is made. This engineering trade study can be designed further for specific application to lightning protection design within the proposed new methodology. Part of Step 7 includes an agreement that the design engineer, the test engineer, and the continued airworthiness engineer evaluate the design configurations from each specialty identified in the trade study survey for redesign or improvement. This Step 7 is a place in the methodology where great advantages can be gained within the design process by evaluating the component performance beyond the qualification test results before the configuration is final. At this point, critical design reviews should be underway in the aircraft development project.

Evaluation of the design should follow in the same manner as the rest of the design reviews already under way.

Step 8 of New Methodology - Assess continued airworthiness against goals

With the results from the lab testing and feedback provided to the test engineer, the continued airworthiness engineer will lead a series of collaborative sessions between the test engineer and design engineer. The structure of this assessment will be provided by the continued airworthiness engineer working within the engineering project team. Some of the key elements to considered during these discussions are:

a. Identify key measures of continued airworthiness (Note that at this level of examination, the inclusion of maintenance errors is not part of the continued airworthiness evaluation). For the continued airworthiness evaluation of this type, it is assumed that the aircraft is restored to its certified configuration at every maintenance inspection. This ensures that maintenance is not applied on an aircraft simply to address lack of training or proper instructions for continued airworthiness. Maintenance should not be applied to increase the level of capabilities that is represented in the type certification.
b. Corrosion level identification and associated rating of the severity. For this a method shall be developed to determine corrosion severity.
c. Electrical conductivity decay over time
d. Security of installations and potential for accidental damage to affect the ongoing performance of the Lightning/HIRF protection. This is a challenge when considering lab set ups that are not representative of the true installed environment.
e. Detection of degradation – link to MSG-3. This includes key indicators of degradation verified by measurement.
f. Comparison to similar parts in service
g. Assessment of installed locations on the aircraft and an evaluation of the actual installed environment against the simulated environment. Along with this input will be the consideration for multiple environmental effects occurring simultaneously and different material interfaces within the particular environmental threat. This information will be passed along by the test data gathering performed earlier in the methodology and contained in the assessment sheets to collaborate the information.
h. Performance of the components under degraded conditions (adequate/not-adequate.) Along with this decision, will be a technical reason for the concern. To improve this determination, additional information regarding the relationship between the installed protection material and finish and the environmental threats is required.
i. Recommendations for revisions. These recommendations will be made based on evaluation of the expected performance, test results and in-service experience. Some key measures of improvement might include:
    i. Hardware improvements
    ii. Material changes
    iii. Installation restrictions
    iv. Sealant additions or revisions
    v. Location changes

Evaluation of the expected performance will also include a measure of whether the design will meet its intended continued airworthiness goals under conditions imposed by the installed environment. One approach is to establish whether the component will be able to perform its duty within the defined maintenance program level goals set by the project. For example, if it is expected that the component may require test every 100 flight hours, this may be found to be incompatible with the goal for tests to begin no sooner than 3000 flight hours. In this case the program goals will require alignment with the component performance capabilities.

Step 9 of New Methodology - Perform design revision studies. Design Change?
The goal of the design option studies proposed within this methodology is to determine if a particular lightning protection design should be revised or improved to meet long-term performance goals. Evaluation of the design alternatives is not a new process for most aircraft manufacturers. However, at this stage in the methodology, the lightning protection components have been selected based on past experience or based on earlier decisions regarding new technology deployment. Evaluations of design optimization have recently included more sophisticated ways to model maintenance cost impacts. Though aircraft system performance (Mean Time Between Failure), operating costs (Fuel, Crew, Landing and Navigation Fees) and ownership costs (the cost of financing money) are well known factors in designing leading edge aircraft, maintenance costs are much more challenging to quantify. Some of the variables involved in calculating maintenance costs include aircraft duty cycles, maintenance skills, technician salaries and union structures, general overhaul and repair philosophy within the airline operations. These factors can create a wide variance in maintenance cost calculations. As manufacturer's maintenance cost models have become more sophisticated, cost studies that include the impact of continued airworthiness into the final trade equation have become a reality. Designs that do not age gracefully impact maintenance cost burden. Thus, the equation for determining preferred design alternatives shall focus on the cost of a revised design in comparison to the life cycle cost of the increased maintenance. A recommended change in the design can be proven to gain value for the future operator and the aircraft manufacturer, provided the assessment includes the expenses associated with the alternative designs. It is not the intention of this research to further expand on the cost analysis within these studies, rather depend on a reliable design alternative tool that considers maintenance costs associated with specific system design alternatives. Further details associated with aircraft maintenance costs and incorporation of equipment trade studies is a separate field of work that is required to support this step in the methodology. Aircraft maintenance represents approximately eleven percent of an airline's operating costs and is therefore a key area in which sufficient thought should be given to by airlines, aircraft manufacturers and maintenance providers alike. However, the maintenance industry is not only a relatively complicated one to understand, but is also one in which determining such costs poses much of a mystery to many. [3.7]
Some of the factors to consider in the alternative design trade studies are:

a. Availability
b. Price
c. Complexity

d. Test data
e. Similarity to current technology or components

For designs that are changed as a result of the trade studies, the process of redefining critical characteristics and test criteria is repeated in Step Three.

Step 10 of New Methodology - Establish final optimized design
Definition of this step is included in Section 3.3 of this chapter. The step description and expectations are unaltered for the improved methodology.

Step 11 of New Methodology - Pass design and test details onto MSG-3 analysis process
The proposed methodology in that is central to this research and development creates a critical link between design and continued airworthiness evaluation. It is most critical to leverage the advantages of including testing and known in-service performance details to the MSG-3 process after the design has been optimized. With this methodology, components that make up the aircraft L/HIRF protection will have gone through an analysis similar to MSG-3 analysis as part of the design evaluation that is developed within the work that produced this thesis. Early continued airworthiness evaluation of component design features provides a great advantage to the design process since conclusions within the MSG-3 analysis will be aligned with the early design review identified in the methodology as Step 4 through Step 9. Key elements within the newly revised L/HIRF MSG-3 methodology [3.5] include identification of L/HIRF protection components, component characteristics, degradation modes expected within the installed environment, and maintenance decision logic for designs that are not considered robust enough to maintain the certification level for the life of the aircraft within its installed environment. The improvement to past practices lies in the early identification of design susceptibility to degradation before final design is established. This is equivalent to conducting a 'mini-MSG-3' analysis within the design cycle as identified in the methodology as an Engineering Detailed Design Tool. The final conclusion of Step 11 for components that are susceptible to degradation is to apply recommendations for applicable and effective maintenance where a design change was not the optimal solution. In cases where the methodology concludes that excellent continued airworthiness performance is likely with no appreciable degradation, no maintenance is selected.

Another input to Step 11 is the results from in-service developmental flying performance data. The input provides intelligence with regard to how components are performing on other aircraft. This performance data is used in MSG-3 to determine robustness of particular components within specified environments for each specific installation location.

Step 12 of New Methodology - In-service and developmental flying feedback to the methodology
Similar in-service performance data can be provided into the design revision studies that are gathered for validation of designs performed by the MSG-3 analysis. Developmental testing of installed components can also be beneficial to design

decision making efforts. Testing new equipment during flight can be a valuable source of information. When performing design evaluations, this information can have a positive effect on decisions with regard to the long term viability of designs. Information on bond path degradation, deteriorated conductivity, increased corrosion and long term security of installation is gathered during the flight tests to augment lab results in the decision making process for new and revised designs. Special conditions for HIRF protected systems developed by the regulatory agencies have driven certification requirements for a continued airworthiness engineering validation program that actively collects data on aircraft protection ground path degradation. Data from these programs are considered proprietary to the aircraft manufacturers and are not readily shared among manufacturers. The data collected however, is very relevant to the feedback identified in this methodology.

3.5 Benefits of a Revised Model

If you compare the methodology proposed within this body of work to the current methodology, you will note four significant advantages in the revised methodology.

1. **The revised methodology integrates the testing together with the continued airworthiness evaluation early in the process.**
   In the current methodology, the focus of testing is typically the qualification of the parts under review. For new or novel components there may be an additional developmental testing performed but this is usually done by a supplier or test engineer responsible for providing alternative solutions for the components. This test data is used for determining the best solution for a particular component to pass qualification and sometimes to last through several environments. It is not part of the current methodology to share this information with continued airworthiness engineers and thus it is rarely taken into consideration when performing MSG-3 analysis.
2. **The revised methodology allows continued airworthiness engineers to input component application assumptions directly into the test plans.**
   The advantage of this approach is to tie direct in-service experience to the design criteria. This is done through collaboration of continued airworthiness and design engineers. A structured interface is required in order to enable continuity of inputs and outputs to this portion of the methodology.
3. **Feedback test results assessments to the engineering test team.**
   The revised methodology accomplishes a new feature in the design process which allows expansion of test result utilization. Feedback from continued airworthiness engineers may result in test configuration changes that add value to the knowledge base and improve the design. This added feature of the new methodology requires close working relationships between the testing community and the engineers responsible for the MSG-3 analysis. Again, appropriate structure for effective communication is required.
4. **Expand the design optimization studies to include evaluation of lightning protection components before commitment to the final configuration.**
   The revised methodology improves the design optimization efforts by including trade studies for lightning protection component installations that would otherwise result in scheduled maintenance. The key to successful implementation of this methodology feature is again communication between

the continued airworthiness, design, and test engineer with the united goal to optimize the design and minimize maintenance.

3.6 Implementation

To implement this methodology, an assessment sheet can be drafted that includes the design information referenced in the above methodology. This information is gathered by an airworthiness engineer and analyzed for optimization of the component design against specific performance criteria that is also included in the report. It is important to understand that each L/HIRF protection component whose failure can affect the continued safe flight and landing of the aircraft should be gathered in one place and included as a series of assessment sheets along with other design data. The design of the assessment sheets is fluid and can take on many different formats. For the purpose of this methodology, a format was designed for the assessment sheets and is applied in the case studies.

Once the basic information of the component is provided, a brief description of the purpose and expected performance of the component is entered under "Component Purpose and Operational Theory". Further in the assessment sheet, the installation data is gathered. This is where important design decisions with regard to lightning current paths and protection availability are gathered. The next general step is to determine the installed environment and potential degradation modes along with mitigations that may be included in the component and installation design. Also entered into the assessment sheet is an evaluation of the testing that was performed. Information on how the component performed under different environmental conditions is stored in the test report to be part of the evaluation of the continued airworthiness expectation. This also includes specific test results and comments from the test engineers. Based on the outcome of this assessment, a redesign of the component or its installation may be sought. Past practices in this regard would rely solely on a successful qualification test. Actual aging characteristics are difficult to model since there is often not a documented degradation of the lightning path electrical properties associated with the aircraft installed environment and duty cycle. The final conclusions of the assessment declare the expected performance for the component and include specific guidance for a design modification that will ensure the best design is in place when required.

3.7 Assessment Sheets

Assessment sheets have been created that correspond to the methodology contained in this chapter. The assessment sheet is exercised in the case studies contained in this thesis. Categories for the assessment sheets may look something like that contained in Figure 3-3 where the most critical information is listed. The use of engineering assessment sheets of this type are part of the new design practice and assist the aircraft designers in applying the method suggested by this work. Appropriate application of the assessment sheets should ensure a practical solution to correcting poor performing designs and inadequate instructions for continued airworthiness. A validation test case is performed in Chapter 4 using actual supplier data for a lightning protection device. Assessment sheets can be designed to include other information supplied by the design team. Prior to deploying this methodology, agreement should be made on what critical information should be contained in the assessment sheets. These assessment sheets act to integrate information from several sources in order to generate good results for the overall design. Flexibility in determining the categories of information that is required can only be provided early in the design program. For this research effort, information that is considered the minimum required to perform the assessment is contained in the case studies. As the case studies were assembled, additional data elements were added to the assessment sheets. This improvement to the assessment sheet will be discussed as part of the Lessons Learned Chapter Six in this thesis.

Engineering L/HIRF Protective Device Assessment Sheet
Protection Component: Radome Diverter Strip

1. Lightning/HIRF Protection Component Data

Name:
Part Number:
Manufacturer:
Design Service Life Goal:

2. Component description:

3. Component Purpose and Operational Theory:

4. Component Schematic and Installation Details:

5. Installation Environmental Threats:

6. Assessment of Critical Characteristics in the Installed Environment:

7. Test Plan Input:

8. Test Data Results:

9. Report from Test Engineer on Continued Airworthiness:
Test Engineer Name:
Report: (include significant findings and relevance to continued airworthiness)

10. Design Revision Request

11. Revision accepted by program

12. Description of final optimized design

Figure 3-3 Engineering L/HIRF Protective Device Assessment Sheet

3.8 Conclusion of the Methodology Development

The methodology developed by this body of work is proposed to improve lightning protection designs and improve the continued airworthiness of these lightning protection designs. In creating the assessment sheets and exercising the methodology, revisions were deemed necessary as learning took place. Actual collection of design details in the case studies proved that the methodology is a valuable consideration for aircraft lightning design development. Though there is flexibility in how the assessment sheets are used within the design community, it is concluded that some sort of organized assessment is required to ensure that the most optimum solutions are implemented during the aircraft development program.

Chapter 4 Validation of the L/HIRF Continued Airworthiness Design Methodology

4.1 Abstract of the Validation Exercise

In order to validate the design methodology presented in Chapter 3 of this thesis, data was supplied by Lightning Diversion Systems Inc to test the theory that the methodology can be applied successfully to new technology lightning protection designs. In addition, the goal of this validation is to determine if indeed, use of the methodology results in new information that can be applied in a new way to the aircraft design process which would not have been previously known information.

As newer aircraft generate more sophisticated L/HIRF design features such as the designs that one may find on an all-composite aircraft, the need to include a new methodology for the continued airworthiness evaluation of these designs becomes centric to the required design practice changes theorized in this research and development activity. The problem of creating L/HIRF protection designs that degrade over time without a method for identifying the importance of the degradation can be solved using this methodology. One key element in reviewing lightning protection designs is that most designs fail latently which means that in may not be known as to whether the continued airworthiness of the component is in place over the life of the aircraft. This creates an emerging challenge in the industry to maintain protection components effectively without the advantage of evident degradation that may be critical to the protection availability. For maintenance technicians, the on-going health of passive devices such as the one included in this validation becomes much more important as voltages generated by the relatively low conductivity of composites structures described in Chapter 1 of this thesis.

Included below is an "**Engineering L/HIRF Protective Device Assessment Sheet**" mentioned in Chapter 3 containing a data set that is intended to prove the validity of the methodology in identifying the significance of the continued airworthiness design criteria to the design where past practices would have only considered qualification tests as adequate evidence of design performance over the life of the installation. Certainly, there is an inherent level of safety provided by components that protect against the negative effects of lightning. Unsafe conditions such as those caused by an inadequately protected aircraft during a lightning strike are to be minimized if appropriate application of the methodology is applied to new protection equipment designs such as that in this chapter.

In this test case below, we will examine a new "segmented" diverter strip design manufactured by Lightning Diversion Systems Inc. This design uses individual metallic segments to direct lightning current away from critical systems under the radome such as weather radar or Inertial Landing System (ILS) antennae. The technology relies on ionization of the segments during the ionization phase of the strike to direct the lightning channel above the segmented diverters and not through the diverters as you would see with solid diverter strips used on many aircraft today.

4.2 Segment Diverter Strip Design Technology

Segmented diverter strips are a lighter weight alternative to standard metal lightning diverters. Rather than conduct the lightning current through the diverters as is done on most lightning diverters today, Lightning Diversion Systems has developed a diverter strip that can redirect lightning and reduce its effects on direct effect lightning damage and in-direct effect lightning electromagnetic interference.

Advantages of LDS Multi-Strike Lightning Protection System

- Permanent, multi-strike protection.
- Negligible effect on RF pattern characteristics.
- Low drag aerodynamics.
- Low maintenance eliminates possibility of catastrophic damage.
- Conductive segments are grounded through resistance material - no arcing between segments during P-static charging conditions. The p-static channel created by the resistance material in the LDS diverter strip eliminates the problems inherent in the design of the foil strip, solid metal diverter bar and internal rod systems.

Sophisticated technology requires congruent safety devices. Pitot boom installations on a nose radome increase the possibility of lightning damage. Damage from lightning striking this type of installation can cause malfunctions of adjacent instrumentation systems. Segmented diverter strips placed on the radome and canopy as in Figure 4-1 allow lightning to travel in an ionized channel above the strip without harm to vital instruments and cockpit personnel. The forces of lightning strokes that sometimes damage conventional protective systems by bowing the permanent strips between attach screws, breaking ground bolts, and breaking diverter strips where right-angle turn occur, are not present when the LDS strip is used. Under Air Force Materials Laboratory Contract F33615-71-C-1380 Project 392-0 (Brunswick Corporation, prime contractor and McDonnell-Douglas Company subcontractor), tests also compared the performance of a conventional solid metal strip diverter with the segmented LDS strip in conjunction with a low-sidelobe antenna housed in a nose cone. The conventional diverter raised the sidelobes typically by 10dB, while the LDS diverter limited sidelobe increase to 1dB - a 35:1 improvement. Radar pattern distortion from signal degradation obstructions may jeopardize the accuracy of early developing airborne pulse Doppler radar systems. These systems rely on extremely low sidelobes to permit detection of targets and to prevent "clutter: in the direction of the ground.

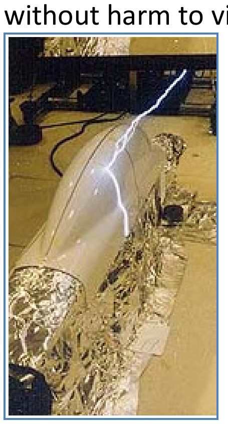


Figure 4-1 Lightning diverting off radome fairing

Extensive testing indicates that the LDS strips will withstand current transfer greater than 200,000 amperes with little or no damage. (More than 99.5% of natural lightning strokes measured display peak current of less than 150,000 amperes.)

Problems with other available systems:

- **Foil strip system -** protects for one strike only as the foil evaporates when struck. Over time, the foil cracks, causing sparks during P-static conditions, leading to severe P-static interference on VHF Comm and NAV frequencies.
- **Solid metal diverter bar system** - protects for more than one strike but at the cost of increased drag and weight. Bars deform during heavy strikes causing radome to buckle. Holes drilled for mechanical inserts often cause cracks and allow moisture in the radome laminate.
- **Internal rod system** - connects to buttons flush with radome exterior and reduces drag problem, but introduces complex fastener design and testing problems because of the magnetic forces developed at rod/button junctures. Rods will bend during heavy strike and damage the radome structure.
- All of the above systems seriously influence the radiation patterns of enclosed radar antennas.

4.3 Validating an Installation

Assumptions are made as to the installation hardware choice that might be selected by the aircraft OEM from previously approved configurations. Within an aircraft design program, this diversion strip hardware is either taken through a qualification test to prove that it meets the minimum certification requirements or shown to be similar to other hardware that is already in use on other aircraft designs and accepted by similarity for certification of the new aircraft. Installation hardware is often not tested alone but rather is tested as part of a component installation simulation in the laboratory. Since hardware of this nature carries the critical task of ensuring the availability of current paths during a lightning or HIRF event, it has become more important for aircraft design teams to recognize the continued airworthiness requirements at a new level of detail. An example of a lightning test setup is found in Figure 4-2. As specific instructions for test set up are left to the OEM lab technician's judgment, installation components such as fasteners discussed in the validation may have a high likelihood of requiring specific test results.

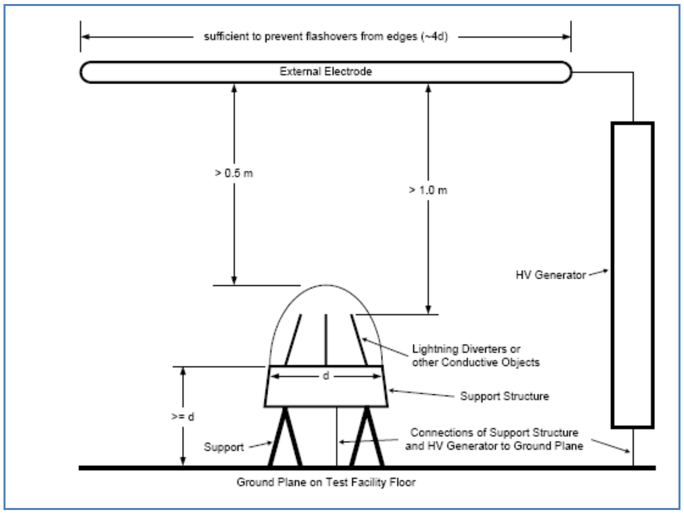


Figure 4-2 Radome Lightning Attachment Test

The importance of installations that provide the continued availability of lightning and HIRF protection, have become much more emphasized in recent industry activities. Early in the 1990's, special conditions generated by the regulatory authorities by way of issue papers, identified a need to recognize the highly integrated nature of new electrical and electronic equipment and the impact that an L/HIRF event could have on the continued airworthiness of those aircraft that had deployed such high-tech designs. At that time, the initial focus of L/HIRF protection was centered on the MSG-3 process and constraints were applied to aircraft that required a continued airworthiness "testing" program to ensure degradation of wire bundle shields and connector interfaces would not jeopardize the continued airworthiness of the aircraft during its design life expectancy. This testing was expected to be conducted by the design holder. Testing of other protection such as diverter strips has also become much more visible with the development of new composite aircraft. Both design practices and continued airworthiness evaluations have struggled to evolve in the years that followed leading up to today as a better understanding of L/HIRF protection is gained and new processes such as the new MSG-3 methodology are deployed within the industry (Ref MSG-3 2007.1). As the methodology for MSG-3 analysis of L/HIRF protection has progressed, so too must the design methodology to account for highly sophisticated L/HIRF protection designs and increased reliance on bonding and grounding for continued airworthiness of critical aircraft systems. This validation demonstrates the legitimacy of the methodology by applying real design data to a simulated design scenario using the "Engineering L/HIRF Protective Device Assessment Sheet" approach.

4.4 An Example of a Completed Assessment Sheet

The example in this chapter starts out with a description of the component and information particular to the component supplier. Data for this description and subsequent information regarding the Diverter Systems segmented diverter strip have been supplied courtesy of Diverter Systems Inc. (ref TTT). As suggested in Chapter 3, a degreed engineer within the design community with background in L/HIRF protection systems may be assigned to the task of completing the assessment sheets for each component that provides for continued safe flight and landing of the aircraft. It is not the intention of the assessment sheets to determine which protection components should be included in the assessments sheets as the certification basis and associated safety analysis are expected to provide the guidance required to identify the components that are important to this assessment. As such, the design community may consider development of a document or internal agreement to be used among design groups that clearly identifies those components whose failure in combination with an L/HIRF event affect the continued safe flight and landing of the aircraft. Assistance from the certification engineer or representative electromagnetic engineering organization is also expected as an input to implementation of this assessment. To aid in this assessment, the document may be created by the department responsible for the compliance to FAR 25.1529 "Instructions for Continued Airworthiness" of the L/HIRF protection. For integrated avionics systems, this document may list all critical and essential L/HIRF protection components. For transport elements such as hydraulic or fuel line tubing, concerns about grounding in areas where a bond degradation can result in fuel ignition or fire can also be considered relevant to the continued airworthiness list. For structural elements, bonding and isolation play significant roles in composite aircraft construction and can be determined to protect underlying critical or essential systems for which these bonds or isolation installation become part of the data package of L/HIRF components. Action of this type is not required by regulatory agencies but may serve as a good engineering practice for consolidation of components that require continued airworthiness instructions to meet certification requirements. This can also aid in identifying appropriate components that require an eventual MSG-3 analysis to be completed. To prove the methodology works, a single component is included in the example below that is verified to be on the list of components that provide for the continued safe flight and landing of the aircraft. In Figure 4-3, the effects of lightning are shown to have caused severe damage to the aircraft nose radome. With proper treatment of the fasteners and installation over time, the effectiveness of the radome diverters can be ensured and result in minimum damage to structure after a lightning strike.

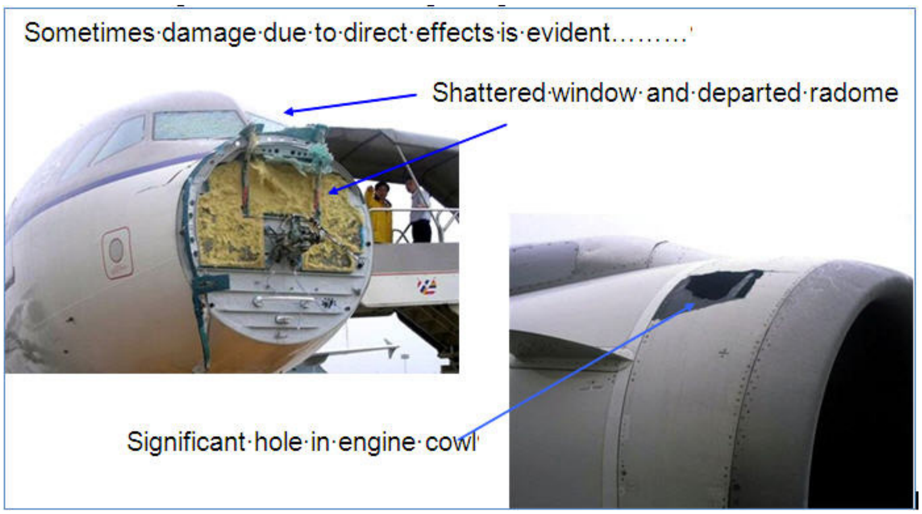


Figure 4-3 Severe Radome Damage from Lightning Strike

4.5 The Assessment Sheet Validation using Lightning Protection Supplier Data

The following data was collected from Lightning Diversion Systems and is a representative data set for what a continued airworthiness engineer would collect on the assessment sheet outlined in Chapter 3, Figure 3-3 Engineering L/HIRF Protective Device Assessment Sheet. The analysis sheet has twelve headings where data is required from the component and installation designers. In this test case, engineering has identified the diverter strips as new technology that protects against the potential catastrophic or hazardous condition due to a lightning strike. From discussions with the design department, we learned that these diverter strips can fail latently and have a potential for common mode degradation as each strip is mounted in the same way using the same installation hardware. This adds a potential for a common mode failure to occur such as the corrosion of multiple diverter strip installations at the same time. With these instructions from the certifying engineer, we start the Assessment by gathering data from the manufacturer and installation designers. Below is a completed assessment sheet.

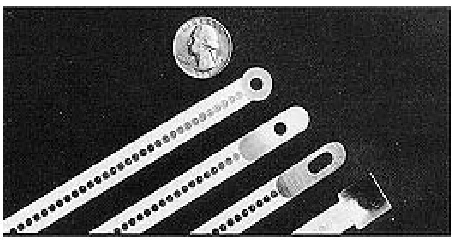
Engineering L/HIRF Protective Device Assessment Sheet
Protection Component: Radome Diverter Strip

1. Lightning/HIRF Protection Component Data

Name: Segmented Diverter Strip (Segment type)
Part Number: LDS 10-01-64-1-SR-01-B-036
Manufacturer: Lightning Diversion Systems (LDS) Inc.
Design Service Life Goal: Life of the installation. Removed only if in a failed condition with no expected periodic removals.

2. Component description:

The LDS™ Multi-Strike Lightning Protection System consists of a thin, flexible, segmented diverter strip that combines 0.10" nominal diameter metal disc segments with appropriate resistance material on a thin (0.005-0.010") laminate.



Lightning Diversion Systems has developed a new and improved lightning protection device that diverts lightning strokes from aircraft nose radomes and other sensitive areas. The protection system consists of a segmented diverter strip which provides maximum multiple-strike protection with negligible effect on RF pattern characteristics. Attached to an aircraft's radome, the system allows a lightning stoke to travel safely and directly to ground in an ionized channel created in the air above the diverter strip. It combines permanent protection with a low drag aerodynamics and has insignificant effect on radar antenna radiation patterns. The electrostatic shield created by the system provides a new source of streamers outside the radome wall to the fuselage. The resistance material in the strips helps initiate the ionized channels and provides a bleed-off path for P-static. The small diameter of the disc segments (1/10 wavelength or less at X band) makes the strip compatible with radar system operation up to and including Ku band. If necessary, disc size can be reduced for optimum antenna patterns at higher frequencies.

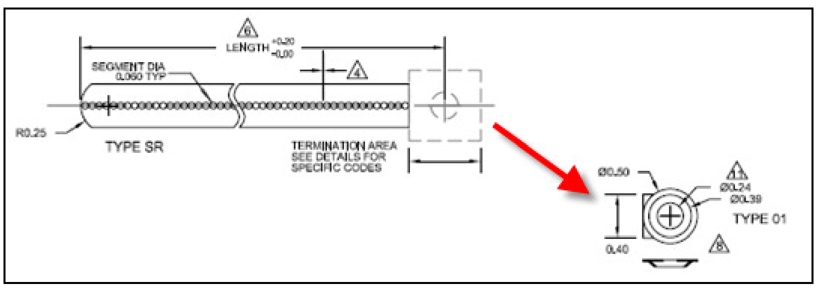
Segmented diverter strips are a series of metal segments connected by resistors on a dielectric substrate. These strips can withstand repeated lightning strikes and can be used on a radome having severe microwave and aerodynamic performance requirements. The diverter strips are normally installed in parallel to the air stream to minimize drag. The spacing between the strips usually will range from 12 to 24 inches depending on the dielectric strength of the radome and the shape and closeness to the radome wall of enclosed metal object.

3. Component Purpose and Operational Theory:

The nose and tail of an aircraft, the ideal location for radar communication antennas, are also the most common targets for lightning strikes. The segmented diverter uses electrical ionization to divert dangerous lightning currents. Radar and communication antennas aboard aircraft and ground based installations are usually contained within a non-metallic radome or other nonmetallic fairings to protect them from damaging airflow and precipitation. Many of these installations are located at the nose or tail of an aircraft where lightning is prone to strike. The metal radar antenna housed within the non-conductive reinforced plastic radome is the main source of ionized streamers created at the nose of the aircraft by high stress fields. These streamers pass through an unprotected radome providing a path for the lightning stroke. When lightning strikes an unprotected nose radome, it can penetrate the radome wall and attach to enclosed metal structures such as a radar antenna. The resulting explosion can cause extensive damage to the radome installation. The installed component protects the aircraft against a potentially catastrophic condition.

4. *Component Schematic and Installation Details:*

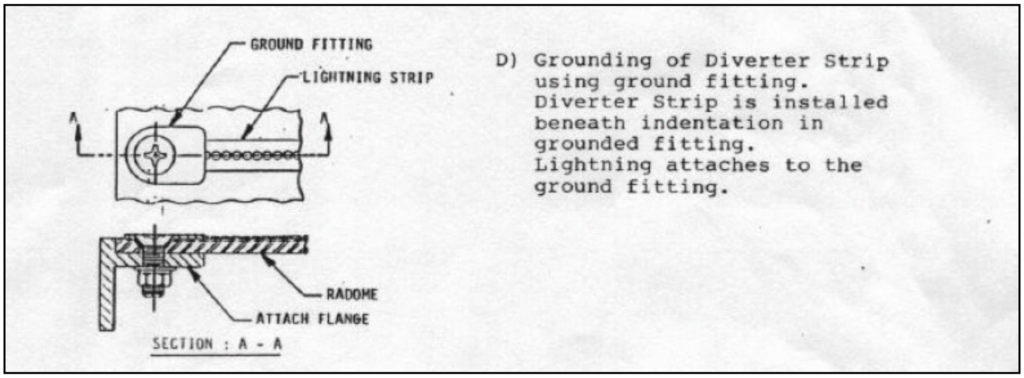
The LDS diverter strips are mounted to the radome by use of adhesive. Diverter strips placed on the radome and canopy allow lightning to travel in an ionized channel above the strip without harm to vital instruments and cockpit personnel. Strips are easily bonded with a compatible adhesive to the outer surface of the radome, and are just as easily repaired or replaces. The strip is attached to the grounding bolt to allow smooth transfer of current.

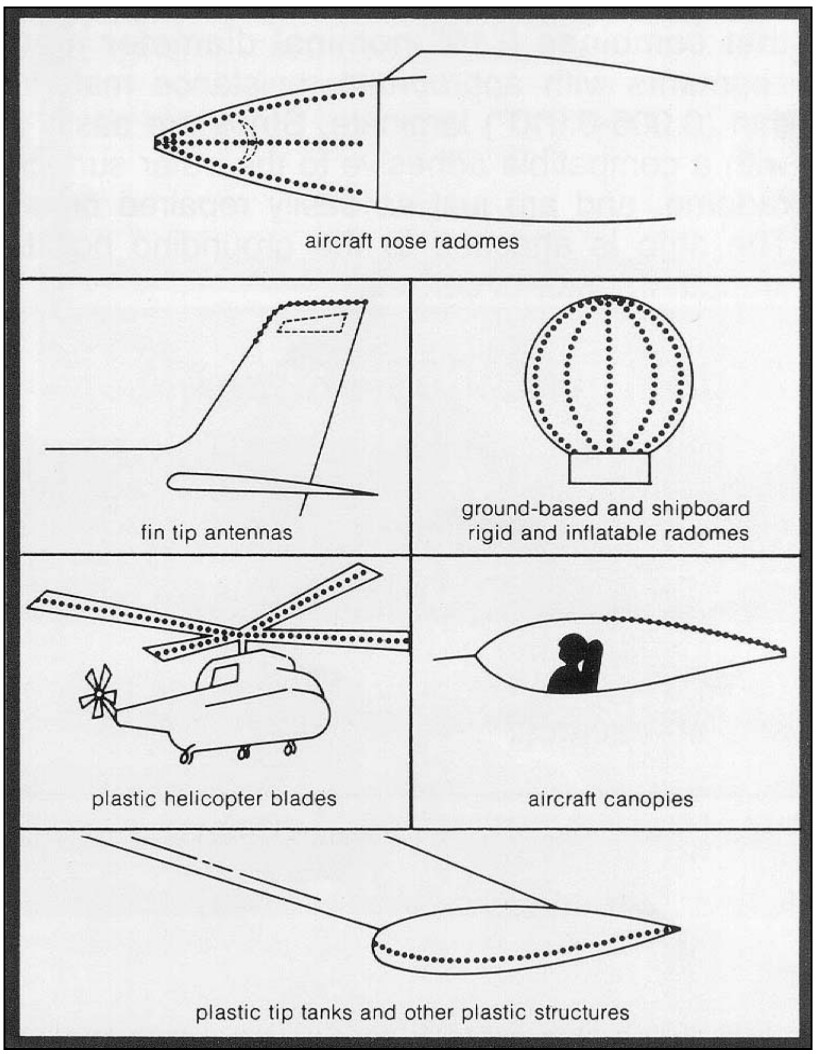


NOTES, UNLESS OTHERWISE SPECIFIED:

1. LAMINATE: EPOXY GLASS per IPC 4101/21, .005 CD HRH/HRH (1/2 oz Cu), PCL-FR-226.
2. ELECTRO-PLATED NICKEL OVER COPPER .0005-.001 THICK.
3. SPLICE AS REQUIRED FOR LENGTHS OVER 48".
4. SEGMENT GAPS TO BE .005 (+.002,-.003).
5. TOPSIDE PAINTED WITH PAINT WLS750 SERIES, OR AS SPECIFIED BY CUSTOMER, COLOR PER FED-STD-595 TO BE SPECIFIED BY CUSTOMER. SEGMENTS TOPSIDE TO BE FREE OF PAINT.
6. LENGTH FROM MOUNTING HOLE CENTER TO FAR EDGE TO BE SPECIFIED WHEN ORDERING.
7. FABRICATE PER LDS SPECIFICATION LDS10-01.
8. WHEN TERMINATION HAS A DIMPLE (100°), SLIGHT IMPERFECTIONS (CRACKING) ARE ACCEPTABLE AT ID OF DIMPLE. CRACKS SHALL NOT EXTEND BEYOND THE COUNTERSINK DIMPLE. STRESS MARKS ARE ACCEPTABLE AT THE TOP SURFACE OF THE DIMPLE.
9. -1 ASSEMBLY, ADD ACRYLIC ADHESIVE 3M A10 9473 PC (0.010" THICK) TO BACKSIDE.
10. TOLERANCES: DEC.XX = ±0.03, DEC.XXX = ±0.005.
11. DIMENSION APPLIES BEFORE DIMPLE.

For bonding the diverter strip to the aircraft, use of the following recommended fastener is applied. The fastener is titanium with a titanium collar (nut). The head of the fastener is countersunk and passes through the dielectric diverter strip into the fiberglass radome and through the aluminum stiffener at the radome base. The collar is self-locking in design to eliminate fastener loosening.





5. Installation Environmental Threats:

- Medium to High temperature swings
- Medium to High vibration
- Medium probability of accidental damage

- High moisture content location
- Exposure to runway and aircraft de-ice chemicals and potential salt spray in marine environments
- Material erosion potential due to contaminants in the air impinging on structure at high speed

6. Assessment of Critical Characteristics in the Installed Environment:

Characteristic	Potential Failure Mode	Mitigation
Nickel plated copper segments mounted to dielectric via adhesive	Corrosion of nickel, erosion of nickel, loss of adhesion to dielectric strip.	Nickel segments are coated to thickness resilient to erosion, adhesive has been tested to exceed all environmental threats found in radome environment
Dielectric strip mounted to radome structure via adhesive	Loss of adhesion between dielectric strip and radome.	Radome is cleaned and sanded during preparation for bonding to supply the most robust bond, heat blankets and pressure bag cures adhesive to appropriate strength for environment. Adhesive properties provide strength required at installation and resist strength loss when exposed to environmental threats of radome installation.
Titanium fastener passed through dielectric material hole, fiberglass radome and aluminum structure to titanium collar (nut).	Deterioration of dielectric material at fastener interface, tearing of dielectric, corrosion of fasteners, loosening of clamping forces on fasteners, cracking of fiberglass radome	Dielectric material is manufactured to withstand tear or deterioration under stress of fastener; **fasteners parts maintain galvanic compatibility with aluminum structure.**

7. Test Plan Input:

Aging aspects of the Diverter Segments that require test investigation are:

a) Nickel resistance to erosion
b) Dielectric strip adhesive robustness
c) Dielectric material resistance to tearing or deterioration
d) Corrosion of fasteners
e) Loosening of fasteners
f) Cracking of fiberglass under fastener clamp up forces and structural loads
g) Delaminate due to moisture ingress or erosion of surface

Life cycle testing should be performed with the most severe environments of the radome installation listed in this report. It is preferred that testing be performed to address multiple environmental threats simultaneously. Please identify capabilities to perform testing in this manner and supply results in test matrix.

8. Test Data Results:

Overall the Segmented Diverter Strips performed well under the simulated environmental threats. Test points assessed by test engineer

1. Salt Spray – Salt spray was increased beyond qualification levels to simulate 20 years of service. Increased duration by 5 times and concentration of salt by 3 times to simulate advanced effects.
    a. Result: Special Attention Item - Advanced corrosion was identified at the fastener installation simulating attachment of radome to aluminum structure. Other diverter components attachment to composite radome showed little signs of corrosion.
2. Vibration – Vibration was applied in accordance with the qualification test requirements with an additional 5 times the duration. This was done in combination with the salt spray test for simulation of true environment.
    a. Result: Good - Diverter installation remained secure in its installation. Torque checks on the fasteners revealed a 5% loss of clamp up force which is within expected range for diverter installations in service. No loosening of the diverter strip was noted in the installed configuration. Adhesive also performed well with no noted gaps in diverter fayed surface to radome.
3. Temperature cycle - Temperature cycle testing was performed to simulate 20,000 cycles from 90 degrees Fahrenheit to minus 60 degrees Fahrenheit. This is expected to be the design life goal representing the aircraft life.
    a. Result: Good – Diverter strip remained intact without deformation.
4. Chemical Exposure – Diverter installation was exposed to 48 hours of exposure to potassium formate (formic acid potassium salt) and then an additional 48 hours of exposure to potassium nitrate to simulate runway de-ice exposure. Though 48 hours exposure was required by direction of the qualification test, two independent cycles of 48 hours was applied to test early signs of corrosion to the same Equipment Under Test (EUT) with successful results. As the probability for runway de-ice in the vicinity of the radome is less probable than within the tire spray areas of the aircraft, this test demonstrates robustness of the installation against this threat. An aircraft anti-ice test was performed with 160 hours of Glycol with some corrosion present to simulate anti-ice formulas used to remove and inhibit ice from forming on aircraft structure. The test exceeded the qualification requirements by four times and was determined to simulate the aircraft life time.
    a. Result: Negative. After exposure to the chemicals as described above, the diverter conductivity through the component and to the structure showed a resistance value of 4.2 milliohms for the runway de-ice test and 5.4 milliohms for the aircraft anti-ice test. Both values are well above the 3.2 milliohm requirement imposed by the electromagnetic effects design requirements for this type of installation.

9. Report from Test Engineer on Continued Airworthiness

Test Engineer Name: Fred Friendly

Report: (include significant findings and relevance to continued airworthiness) The most significant finding was the propensity of this design to corrode under exposure to chemicals beyond the qualification levels. After further investigation, it was found to result in a failure to meet the “end of life” installation resistance.

Though Qualification Testing may have passed using assigned qualification testing exposure levels, it is understood by this test that re-evaluation of the design may be prudent. The area most suspect for consideration of revision is the fastener attach point to the simulated aluminum structure where visible corrosion was noted.

10. *Design Revision Request*

    Yes. Revise fastener from bare Ti to corrosion resistant Cadmium plated Aluminum fastener and collar. Conductive properties are expected to remain in tack and galvanic compatibility of Nickel plated copper diverter strip to bare aluminum structure is expected to also remain minimal. Re-test requested.

11. *Revision accepted by program*

    Revision of installation fasteners considered acceptable to avoid unnecessary maintenance of the diverter strips. Proceed with design revision notice to the affected engineering organizations.

12. *Description of final optimized design*

    The diverter strip installation can be optimized by inclusion of a cadmium plated fastener to eliminate potential maintenance of the previous design over the life of the aircraft. The fastener revision is expected to have a low impact on design costs and high impact on improved continued airworthiness performance.

4.6 Conclusion of Validation

From the outcome of the assessment sheets, it can be concluded that identification of the galvanic incompatibility of the installation fastening system would not have been included in the design criteria with the current design practices that are in place. Given that the current design practices would leave the assessment of the installation to the MSG-3 analysis conducted later in the development process, maintenance may have been applied to this design implementation and not considered as part of the fundamental design methodology. Without this assessment in place, data gathered during the testing phase and included in the Assessment Sheets may also have been inadequate to properly assess the continued airworthiness of the component in its installed environment over the life of the installation during a subsequent MSG-3 analysis. If the MSG-3 analysis is improperly informed regarding the design installation and maintenance is not applied, a potential degradation of the bond provided by the segmented diverter component could affect the ability of the aircraft to protect itself from the unfortunate effects of a lightning strike. This lack of appropriate connection between the design and continued airworthiness can be bridged using both the methodology contained in this body of work and the assessment sheets recommended in this chapter. The segmented diverter is considered new technology when compared to solid bar diverters. Segmented diverters are lower profile, lighter and easier to maintain. Though the example using a segmented diverter is quite rudimentary, more complicated designs such as the grounding techniques for components that penetrate fuel tanks through composite structure are much more challenging to determine an effective continued airworthiness design. It is expected that the assessment sheets will both: 1) enable the methodology and 2) create conclusions for the design of L/HIRF protection that are not currently provided in any way by the design practices used today.

Chapter 5 - Introduction Case Studies (Non-Proprietary)

The following section represents a non-proprietary version of the case studies supplied to Cranfield University required for this PhD thesis. The proprietary case studies have been supplied to the supervising professor (Professor John P. Fielding) at Cranfield and developed by the student under a Proprietary Information Agreement between Cranfield University and the aircraft manufacturer.

5.1Case Studies – Aircraft Lightning Protection Design Analysis of an Aircraft

The case studies demonstrate how to apply the aircraft Lightning/HIRF Protection Continued Airworthiness Design Methodology to a derivative model of a large transport aircraft that is in operation and examines whether the design methodology could produce the expected results of reducing poorly performing designs during the design phase of an aircraft development project. Several case studies have been created in this section to test the viability of the methodology across different types of lightning protections. An analysis of lightning protection component designs and the application of integrated engineering processes are performed in these case studies using structured design evaluation sheets and aircraft component data. Results of the studies included in this chapter are intended to provide evidence that the methodology proposed in this work is valid for developing the lightning protection continued airworthiness component designs. The studies rely heavily on a data set consisting of lightning protection designs provided for aircraft looms, electrical and electronic equipment, aircraft structure and system components.

The data set has been modified to protect the proprietary information and may be considered hypothetical data used to exercise the methodology. Actual valid design data was used to test the methodology and is contained in a proprietary Appendix.G. Results are obtained on the application of the methodology while limitations of the data are also discussed. Though the design data presented is associated with and already completed and approved design, the case studies also seeks to prove the application of a design methodology on a new aircraft development program. In a new development program, one would apply the methodology along with the concurrent engineering activities already in place for each phase of the development program. Aircraft design phases can be divided into the following distinct stages:

1. Conceptual Design
2. Preliminary Design
3. Detailed Design

Finally, a conclusion is provided as to the practical application of this research and the possible impact of the new design methodology. Continued study of this concept and applications of the methodology are discussed as future work in Chapters Six and Seven of this thesis.

5.2 Including "Continued Airworthiness" Within the Aircraft Design Process

In the case studies performed by the author, "continued airworthiness" is established as a branch of the design process which requires consideration for the methodology defined in Chapter 3. Aircraft design is created using an iterative process using inputs such as:

- Mission definition
- Performance requirements
- Initial sizing
- Configuration layout
- Design alternative trade studies
- Regulation compliance and certification
- Safety analysis

Within a given aircraft development program, design phases are created that serve the purpose of bringing the design to a more conclusive and concrete configuration as it develops towards maturity [5.6]. There are a number of generally accepted stages in the design, development, manufacture and operation of aircraft, each with associated methods and data requirements. Though there are typically defined design phases, development of an aircraft design is an iterative process where one design phase sometimes flows seamlessly into another as designs are created, evaluated, abandoned and new design solutions created. From different designer's perspectives, one receives differing views on which certain design processes lead or follow other design processes. Requirements are established after a team of engineers and technologists determine the overall goals of the program to meet the customers and Original Equipment Manufacturers required payback. Performance requirements are firmed up in this stage as the conceptual phase of the program dials in on a final committed mission. It is in this conceptual phase that requirements are developed which influence many of the early decisions. Within the requirements development activity, the design process should consider the continued airworthiness of the airplane by ensuring that assessments are made along the way for deterioration of critical components within the installed environments. Service experience with component designs and materials should also play a role in the conceptual design creation. A major tenant of this body of work is to emphasize the importance of including continued airworthiness throughout each aircraft design phase. Figure 5-1 depicts one view of the different design phases and the specific activities that are typically conducted in each phase [5.7]. Historically, the necessary aircraft support and initial minimum required maintenance program is established after the detailed design is complete as shown in Figure 5-1 and after initial aircraft fabrication is complete. Newer generation aircraft development programs have found great value however, by including maintainability and reliability as part of the concurrent design teams efforts within all the phases of the design process. It is important to note the iterative nature of aircraft design; where design concepts are generated and then evaluated from many design perspectives, including cost and produce-ability, creates opportunities to establish the "right fit" design to the final configuration. This opportunity within the design process to create better operating and longer lasting designs also applies to designs for lightning protection. The important thing to the lightning protection engineer during the conceptual design phase is the decisions regarding general geometry of the aircraft and material selections. For example, if it is determined within the conceptual design phase that the aircraft will use composite materials in certain specific applications and locations, it then becomes important for the lightning protection engineer to include the appropriate lightning protection within the conceptual design evaluations. This decision can also potentially generate a need to test different lightning protection solutions. These tests and designs require certain evaluations for the continued airworthiness of the installed equipment within the conceptual design phase. A similar example can be demonstrated with the final aircraft geometry. Certain extremities of the aircraft are exposed to more significant lightning strikes as demonstrated by lightning protection design practices and models run by the lightning protection design engineers assigned to the project. These geometric decisions should include potential options for the appropriate lightning protection so that good preliminary designs can be achieved. As designs are submitted and the conceptual phase is complete, additional preliminary assessments of optional protection methods can be evaluated within the preliminary design phase.

5.2.1 Conceptual Design

In the conceptual design phase, general concepts for design are created. Materials may be determined at this point but attachment techniques and specific dimensions may not be determined. If the material is composite, the lightning engineer may begin the process of determining the appropriate measures that are required to adequately conduct electrical currents associated with a lightning strike event. This information is shared with others on the design team and the iterative process of design is put into motion. Testing may be necessary and plans for qualification need to be initiated. Interactions among engineers with responsibility for different components that rely on the design are most important at this phase. At this point in an aircraft development program, designs are very fluid and quick response to the impacts of differing designs requires support from both the engineering staff and the engineering design tools that are utilized. Requirements generally drive the design development at this stage but requirements may also be revised if it is determined that the original goals no longer apply or that the physical solution forces different constraints than originally envisaged as in the case of a composite structural member in place of a metallic structural member discussed in this example. The lightning protection continued airworthiness methodology described in Chapter Three of this thesis includes activity within the conceptual design phase of the development program where issues such as service life, scheduled maintenance goals and maintainability are influenced.

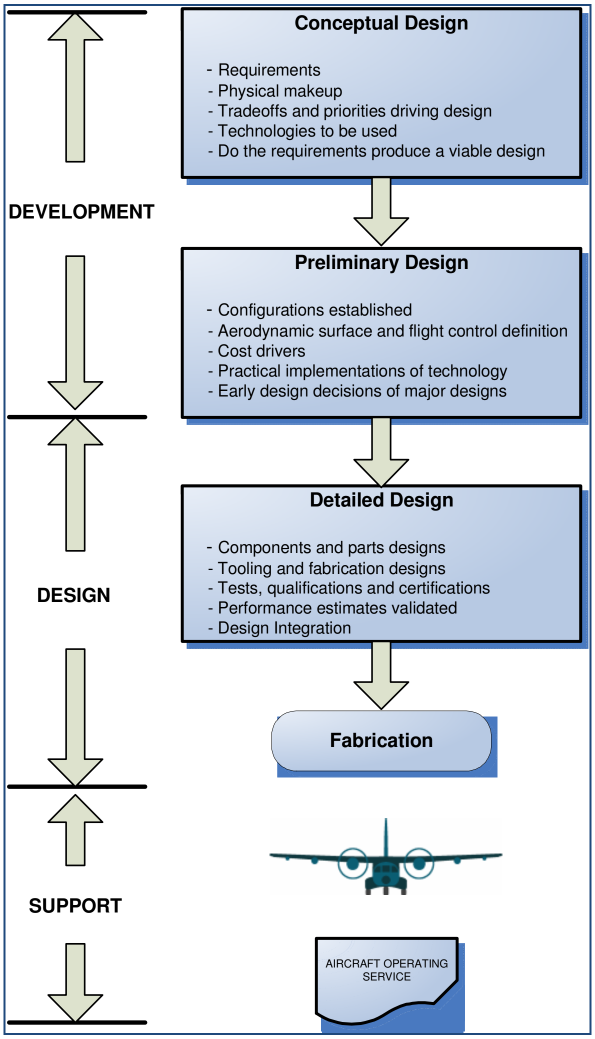


Figure 5-1 Aircraft Design Phases and Activities

5.2.2 Preliminary Design

In the preliminary design phase, major changes to the design are not expected. Major geometry and physical arrangements have been decided at this point in the development program. At this stage the designs begin to mature. Major studies that drive major configuration changes are no longer tolerated. The goal during this phase of the program is to start the design freeze process in all areas of development. Analysis of details associated with the designs takes place that generate early specifications that can be reviewed by design teams and offered to suppliers that may play a role in the development of the aircraft components, systems and structures. The weight of design alternatives is now used as a measure of the expected design success. Performance is heavily involved as a determining factor for certain preliminary design decisions. In the lightning design, solutions begin to be created and tested. In this phase more details can be developed without the concern for quick changes invalidating the design on a large scale. The lightning specialist is active during this phase developing potential solutions for protection designs based on the requirements. Interfaces between performance, structural and systems designers are formalized during this phase as individual design experts share their individual design solutions with other area experts to determine longer term viability of the design interfaces. In this phase testing, modeling, mock-ups and software simulations are created. Software design tools are shared as well that allow individual engineers to create studies and different design solutions for evaluation. Ultimately, the preliminary design creates a platform from which detailed designs can be created. Reaching this platform is a crucial point in a design process that may be measured by the number of formal and approved drawings that have been released. Specialists in areas such as maintenance cost, reliability and maintainability are heavily involved in the early part of preliminary design to ensure that the final product meets its business goals in availability and dispatch reliability as well as continued system performance. Decisions such as structural buildup, fasteners, fastener hole preparations, sealants required, material compatibility are not determined at this phase.

5.2.3 Detailed Design

In the detailed design phase, all the required aircraft parts and systems enter into a more controlled configuration environment. Changes to designs may be more formal and added administration ensures that the individual designs of components can integrate with other detailed designs that are also maturing, sometimes simultaneously. Actual dimensions and material makeup and component interfaces are decided and documented in a central engineering function using many design tools for structural configurations, functional specifications documents, and wiring databases as an example. Locations of holes that must be cut out, incorporation of particular fasteners for specific applications and dimensions become fixed in this phase. For lightning protection, specific materials are chosen to ensure conduction of lightning currents, wire looms may by optimized for lightning attenuation using design tools to determine the amount of attenuation that is required and then choices are made regarding the systems shields that might be routed along with the looms. Such things as brackets, loom clips, avionics racks, doors and window dimensions and locations are all relevant factors to the lightning protection designer. Ignition prevention is important to protection designers and specific measures to avoid charges than can create an ignition source are developed, tested and implemented. During this phase, fabrication and tooling engineers interface with the aircraft designers to determine the most efficient and successful way to build the airplane. Most of the detailed testing can now take place as the final decisions for parts and components are in place.

For lightning protection, deterioration of components such as earthing jumpers and electronic looms shielding for example, can lead to lower lightning protection effectiveness. Ensuring that the designs last for the life of the aircraft goes beyond the typical reliability and maintainability focus.

Lightning protection design and consideration is an important part of each of the three design phases describe in Figure 5-1 and should be integrated into the design development program. Incorporation of lightning protection design solutions within each of these phases can be achieved by use of integrated design teams. This approach embraces the teaming of functional disciplines to integrate and concurrently design aircrafts with input from individuals from multiple design disciplines. In this way, decisions are made closer to the design community responsible for the ultimate design. In many integrate design teams, representation draws from customers, product sales, process engineering, production and test engineering. The organization of these design teams can be done many different ways however the key to a design teams' success is the ability for an integrated design team to make decisions locally that meet customer and performance criteria. These teams may also evolve throughout the design process as different issues emerge that require more focus. The lightning protection engineering community operates across many different design disciplines and requires careful thought for how to organize within the design development teams to be effective. The most important strategic tool for designing a "well-built" product is the effectiveness of the communication. Within the case studies that were created as part of this body of work, it is suggested that the new methodology for the design of aircraft lightning protection components relies on communications and assessment tool such as the, "Engineering L/HIRF Protective Device Assessment Sheet". With the proper organizational structure in place, these lightning protection device assessment work sheets can become part of the design tools used to develop a product that meets the design criteria listed in the original requirements. Within this structure, the lightning protection engineer will have access to experienced aircraft designers within many disciplines such as electrical design, propulsion design, avionics, systems, wire installation, electrical standards, structures and electrical power. This allows team members to learn from each other and develop a collective knowledge on the most effective design solutions to incorporate. The use of a concurrent design process will aid in the success of the new design methodology proposed by this work. Concurrent design activities create long lasting relationships among designers throughout each of the design phases. The concept of creating a concurrent design organizational structure crosses design phase boundaries and includes some of the same design experts in all of the design phases. Within the concurrent design organizational structure, it is important to consider lightning protection continued airworthiness within each design process phase. It has only been in recent years that the continued airworthiness of lightning protection became a significant part of the design and certification processes. With the lightning protection designers brought into the earliest stages of the design process, benefits are realized including, reduced manufacturing costs, better product quality and fewer late design changes.

Using the new design methodology, assessment of the aircraft design may generate different results than the already certified design in the case studies. Comments on the findings regarding design decisions will be made to the best of the authors ability with the understanding that the data set used is already certified where appropriate action has been taken to address the design issues to the satisfaction of the designers and the regulatory authorities as part of previous certifications.

It is understood that the airplane was designed to the best standards at the time of its original production and certification. Using the new methodology and design data in the case studies is expected to demonstrate differences in the outcome of the design process that may have a positive impact on the final design implementation.

5.2.4 Revolutionary Designs

Revolutionary designs are higher risks, requiring testing to prove technology. This may include rig tests, ground tests, and so on. Composite primary structures are a good example of revolutionary designs being put into practice. The direct effects of lightning may cause the industry to adapt to new and revolutionary repair procedures that address composite structures. For composite aircraft, fuel tank protection may be a major departure from past aluminum designs. Higher voltages caused by higher resistance in the composite structure need special attention and designs. Wireless flight controls within an airplane would be a revolutionary approach to past fly by wire or cable and bell crank designs. These revolutionary design concepts would require special consideration of the effects of electromagnetic threats and possibly generate revolutionary protection. Fiber optics is also a revolutionary way to transmit and control aircraft flight. The methodology proposed in this work would cope with these revolutionary design approaches by ensuring that bond paths and components put in place to ensure the continued safe flight and landing after a lightning event are robust for the life of the aircraft. The methodology will demonstrate its application to a revolutionary design by addressing the composite structures as an example in the data sheets. This will exercise the methodology in search for any possible improvements required.

Specifically, this work proposes the new methodology for determination of improved designs during the design phase of an aircraft development program [5.9]. The new methodology for which these case studies demonstrate application has also been submitted to the US patent office for potential patent protection under the title, "Methods and Systems for Evaluating a Design of an Aircraft". Whether the designs created through use of the methodology theorized in this body of work are revolutionary or evolutionary, the application of the new design approach for which the case studies are developed can be applied in either case. Creation of revolutionary designs is driven by the need to create innovations that bring benefit. Evolutionary designs are step improvements to existing designs that also bring value to the final product. Both evolutionary and revolutionary designs are driven by the need to solve a problem. The case studies conducted in this body of work seek to solve the problem of including the constraints of continued airworthiness for lightning protection components within the design process for those components. As described in Chapter 2 of this thesis, the increased use of "fly-by-wire" technology for communication between aircraft avionics and flight control systems brings greater concern for the accurate transmission of control signals between systems on airborne aircraft. Industry standard [5.3] RTCA/DO160 "Environmental Conditions and Test Procedures for Airborne Equipment" which defines suggested means for testing the electromagnetic effects on aircraft systems and appropriate test levels addresses early concerns regarding the safe operation of aircraft that rely on digital communication methods for aircraft control. ARINC (Aircraft Radio Inc.) has created a protocol for avionic equipment communication called ARINC 429 which is a signal protocol used to transmit data between critical avionic equipment [5.4]. Failures of fly-by-wire systems data signal interfaces are unacceptable. Surges associated with lightning strikes require protection at signal line interfaces to provide reliable continued performance from damaging voltage spikes. In aircraft systems, ARINC

429 signals are widely used to transfer critical data including airspeed, temperatures, tire pressure, center of gravity, fuel weight, engine operating performance and other critical functions. Interconnections of twisted pair wires are shielded by use of a conductive wire incorporated into the wire loom to reduce the effects of both communication noise and induced lightning effects. Designers refer to RTCA-DO160 in order to acquire the proper waveforms for lightning threats that drive out appropriate protection designs such as wire shielding and current suppression.

The creation of “manned flight” vehicles revolutionized transportation. In this respect, an aircraft could be called a disruptive technology [5.8]. Disruptive technologies change the way an industry works. The term disruptive technology was coined by Clayton M. Christensen and introduced in his 1995 article, “Disruptive Technologies: Catching the Wave”, which he co-wrote with Joseph Bower. Disruptive technology could be manifested through an innovation that improves a product or service in ways that the market does not expect, typically resulting in some benefit to the market, the environment, or the system in which the product operates. Disruptive technologies spring from innovations that create a new market by applying a different set of values.

"Low-end disruption" occurs when the rate at which products improve exceeds the rate at which customers can adopt the new performance. Therefore, at some point the performance of the product overshoots the needs of certain customer segments. At this point, a disruptive technology may enter the market and provide a product which has lower performance than the incumbent but which exceeds the requirements of certain segments, thereby gaining a foothold in the market. In Figure 5-2 this is demonstrated by innovations that enter markets and offer increased value that moves a Low quality user demand to a Medium quality user demand and over time ultimately drives markets and performance to higher levels creating more demand for the innovation. Composites used in aircraft designs have moved along this type of curve as early applications show value for designs such as lighter rudders, more durable wing tips and control surface panels. This led to more widespread applications in propulsion nacelles and fuselage sections.
In commercial flight business, many customers are happy to board the plane and get to their destination at the lowest price, even if the comforts of other types of transportation such as a train or long haul bus which may offer wider seating that is typically not part of the flight experience. This type of customer is not willing to pay a premium for enhancements in product functionality. Perhaps this is one of the underlying factors that have driven the standards for the fight experience. Once the disruptor has gained foot hold in this customer segment, it seeks to improve the profit margin. This may drive aircraft manufacturers to develop more efficient aircraft that cost less to maintain while also creating design improvements in the passenger experience. The methodology proposed in this thesis seeks to create a better product by improving lightning protection designs during all design phases of the project. To get higher profit margins, a disruptor needs to enter the segment where the customer is willing to pay a little more for higher quality. New aircraft features such as larger windows, reduce cabin pressure driven by the advantages of composite structures may drive a revision to passenger willingness to pay more for a

flight on this newer designed aircraft as compared to metal aircraft designed and developed in the 1990s. To ensure quality in its product, the disruptor needs to be innovative. Widespread use of composites can be considered an innovation but is probably not a revolution for the airline industry. The incumbent aluminum aircrafts will not do much to retain its share in a not so profitable segment. Aluminum aircraft products however will have to move up-market and focus on its more attractive customers by offering more cost effective features such as removing fees for luggage. Without the disruptive technology offered by the composite aircraft, aluminum aircraft designs may find that it cannot deliver an entirely similar experience to its customers and will not be able to move up the disruptive technology curve shown in Figure 5-2 as effectively as a composite technology product. After a number of such encounters, the incumbent will be squeezed into smaller markets than it was previously serving in lower performance level markets. At that point, finally the disruptive technology meets the demands of the most profitable segment and drives the established product out of the market rendering all new aircraft designs with similar composite applications.

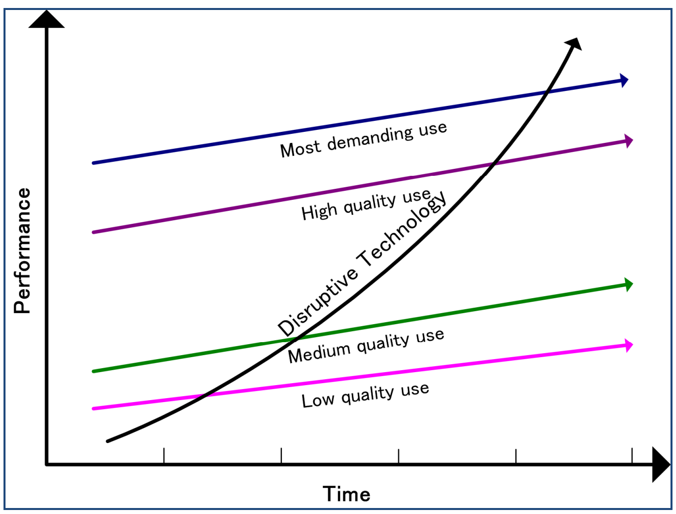


Figure 5-2 Disruptive Technology – Used to Create Increasing Value Over Time

5.3 Case Studies Description

It is intended that the methodology and results of this design analysis will be applied to new aircraft designs. The data used in the case studies is gathered from already determined designs, however, in a new aircraft development case, data would be gathered concurrently with the design development process. The data set used in the studies includes lightning protection device information that protects against either direct effects or in-direct effects of lightning strike and is representative of most airline aircrafts. Included in the data set is information regarding the lightning protection physical characteristics and installation information for systems or structural protection installed on the aircraft. As described in Chapter One of this thesis, lightning protection is provided to eliminate the potential harmful effects of lightning due to direct attachment of lightning “direct effects” and indirect effects associated with electromagnetic coupling or “indirect effects”.

5.3.1 Assumptions

Lightning protection design and certification relies heavily on past successful design measures and certification documentation. In the case of the large transport aircraft used in the case studies, references to past designs and past certification assumptions are made during the new design development project in order to establish the baseline from which to develop the new aircraft. It is important during a new aircraft design process to remain cognizant of the past assumptions and in some cases such as the large transport aircraft used in these studies, reference past certification documentation to better understand the design decision making process. In many aircraft design development programs, designs and certifications for previous unrelated aircraft may also be used due to the successful performance and certification of those designs. The case studies will include design information that may be new design concepts or past designs that have successfully been incorporated into other aircraft designs.

As discussed earlier in this thesis, lightning strokes are electric arcs between oppositely polarized charge centers. The centers may be contained within a single cloud, within widely separated clouds, or within a cloud and the ground below. For airplane protection, it is recognized that cloud-to-cloud and cloud-to-ground strokes occur and that an airplane may form a portion of the discharge path. Furthermore, the discharge may approach the airplane from any direction.

The presence of an airplane in the electric field between charge centers has little effect upon the onset of lightning. Between closely spaced intra-cloud charge centers, an airplane may distort the field sufficiently to induce lightning, but generally the physical size and electrical capacitance of an airplane are small compared to the geometry of a thunderstorm. As a result, the airplane generally will have no effect on the cloud charge. The discharge path may be altered slightly by the presence of an airplane because of the airplanes conductive skin, but it does not measurably influence the charge transferred or the maximum stroke current.

Conversely, virtually nothing can be done to prevent 1ightning from striking an airplane short of diverting from the known weather patterns containing lightning activity. If an airplane enters the intense field between charge centers, it is impossible to charge the-airplane sufficiently to repel a lightning stroke or to prevent the discharge from occurring. Likewise, efforts to avoid thunderstorm activity are rather futile as the opposite charge centers may be widely separated and the-probable discharge path is not obvious. One must accept that if a commercial airplane service is to continue during periods of inclement weather, that the chance of lightning strikes to an airplane must be accepted. In general, it is accepted that large transport commercial aircraft are struck by lightning approximately once per year or once every 3000 flight hours as discussed in Chapter 2.

In early days of commercial flight when the lightning strike to aircraft phenomenon was less understood, it was first thought that jet transports would not suffer as many strikes since they would normally fly above lightning activity. While jet airplanes do spend the majority of their flight time above normal lightning activity, a sufficient number of strikes occur during ascent and descent so that the average number of strikes for jet airplanes is nearly the same as that for propeller airplanes that spend most of the operating time at lower altitudes. In assessing the lightning strike susceptibility of the large transport aircraft in these studies used to drive lightning protection design, it is anticipated that the aircraft will experience the same strike rate as that of the other aircraft produced by the manufacturer of the aircraft used in the case studies. With this in mind, early experience with these other large transport aircraft may drive some lightning protection designs known to be effective using the earlier model aircraft experience.

5.3.2 Strike Locations for the Aircraft in these Case Studies and Probabilities

Certain portions of an airplane are more likely to be struck by lightning than other areas. Those regions of small radius of curvature, particularly near the extremities where maximum electric field distortion occurs, are the most probable attachment points. Experience gained with other airplanes has shown that the probable strike points can be accurately predicted. The distribution of strokes to the aircraft under study is expected to be nearly the same as that experienced on the previous aircraft designed by this manufacturer since wing mounted engines are used along with a conventional tail assembly group. This assumption is part of the driving factors that assist in creating the new aircraft lightning protection schemes.

Lightning swept strokes occur as a result of airplane motion with respect to the ionized stroke path. This phenomenon is described in more detail in Chapter Two of this thesis. Swept strokes create multiple lightning strike attachments to the aircraft, usually seen as burn marks along the fuselage where the lightning temporarily attaches to the structure as it is “swept” along the body of the aircraft while the aircraft moves through the lightning event. Most lightning strokes consist of more than one discharge through the same path. The ionized path remains nearly stationary as the airplane moves forward; hence, the subsequent discharge within the original channel strikes the airplane aft of the initial attachment point. Most airplane lightning strikes are swept aft, with pit or burn marks along the skin defining the track the stroke has taken during the swept event. The Federal Aviation Agency has defined those surfaces where initial attachment is likely as lightning Zone 1 surfaces; where swept strokes are likely as Lightning Zone 2; and those surfaces where strikes are not apt to occur as Lightning Zone 3. Applying the FAA description of Lightning Zone 1 surfaces to the large transport aircraft in these case studies, the areas of highest probable stroke attachment are in lightning Zone 1. This is consistent with the findings of the report demonstrated in Figure 5-3 (chapter 2 Reference [2]). The nose, up to the junction between the radome and body; wing tips; forward and aft projections of the engine nacelles; flap track fairings; and tail group extremities are Zone 1 surfaces. The Zone 2 surfaces, where swept strokes are 1ikely, include the entire fuselage; along the wing to a specific number of inches either side of the engine forward projection and another specific number of inches inboard of the forward projection of the outboard end of the leading edge slats. It is unlikely that lightning will strike either the inboard edge of slats or the leading edge flaps as they are shielded by the engine nacelle and the fuselage. The remaining surface areas are classified as Zone 3 as they are not likely to be struck.

The probable stroke distribution in on the aircraft in these case studies is based upon Figure 5-3 representing aircraft experience gathered by manufacturer experience and data obtained from text book (chapter 2 Reference [2]) as shown. This distribution was determined from model studies conducted by the manufacturer as well as from actual service experience. It should be noted that the stroke distribution shown in Figure 5-3 indicates only the probable initial attachment point. Areas aft of the initial attachment point may be subjected to swept stroke lightning.

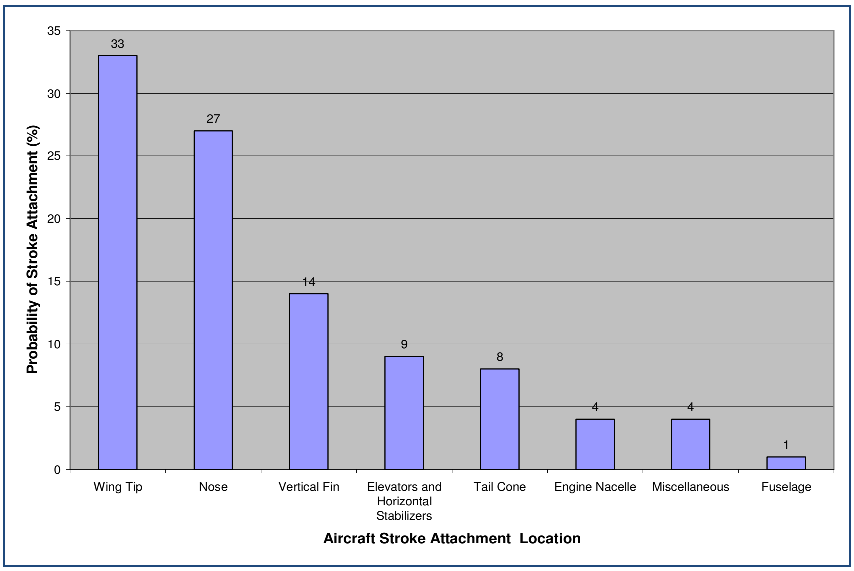


Figure 5-3 Probability of a lightning stroke attachment to a transport aircraft

5.3.3 Aircraft Design and Certification Approach Affecting Case Studies

Though these case studies use a certified aircraft design basis for demonstrating the design methodology presented in this body of work, some of the certified designs were approved through use of other similar designs on either the previous earlier model aircraft or through use of similar design aircraft on other earlier certified model aircraft. In other cases, even more modern aircraft design certification is referenced for approval of some portions of the aircraft lightning protection contained on the aircraft in the case studies. Understanding this method of certifying aircraft systems and lightning protection components, it can be concluded that the use of the lightning protection continued airworthiness design methodology presented in the case studies can bring benefit to both new designs and older already certified designs.

The aircraft in the case studies was designed to incorporate all necessary lightning direct effects protection measures. This hypothetical aircraft is a derivative aircraft, and so many of the components of the aircraft have been previously certified for direct lightning attachment on earlier models of this aircraft. In cases where the protection design within these case studies refers to previously certified components, data will be included for the earlier aircraft design data. In the original certification proposal for the aircraft in the case studies, a lightning protection certification document was supplied to the regulatory authorities. This document is referenced in later certification documentation as the foundation for the design selected and is used to generate pertinent assumptions for lightning protection components certification.

The large transport aircraft design in the case studies will re-certify existing components with similar installation by test or suitable service history justification which will also be included within the case studies when appropriate. Verification of new or significantly modified components, or ones that are significantly affected by modification, will be completed by analysis and/or test. In addition to direct effects protection incorporated as essential to maintain safety-of-flight, there may be features incorporated to achieve design objectives developed by the manufacturer for minimizing the frequency of minor repairs.

Any new or significantly modified component, or one that is significantly affected by modification, that could be affected or influenced by direct lightning attachment, including structural members, components, or surfaces, is addressed in the certification reports and was also addressed in the design development.

Any new or significantly modified system, or one that is significantly affected by modification, whose failure would cause or contribute to a failure or function that would prevent continued safe flight and landing or whose failure would reduce the capability of the airplane or ability of the crew to cope with adverse operating conditions that could be affected or influenced by induced lightning transients is covered in the lightning protection certification. The referenced manufacturer document titled, "New and Significantly Modified Systems, Equipment, and Components" [5.21], contains a list of all systems that are new, significantly changed, or significantly affected by change. Note that all LRUs within a new or significantly modified system need not necessarily be new or significantly modified; a system can be modified and still retain some unchanged components. Also note that a given LRU may be a component of multiple systems.

The following definitions were used in arriving at a list of systems that are new or significantly modified System, or are significantly affected by change, together with a summary of the LRUs that comprise that system (the System Boundary).

New or Significantly Modified System - A "new" or "significantly modified" system is one that performs a new function, or that performs a function comparable to one on the existing transport aircraft but whose implementation has changed enough to negate the validity of extrapolation or use of analyses or tests that were used to show compliance of the previously certified system.
System Significantly Affected by Change - A system that is significantly affected by change is one that, although not new or significantly modified itself, can no longer rely on extrapolation or use of analyses or tests that were used to show compliance of the original or previously certified system due to changes in other systems. The significance of a Significantly Affected system drives the design community to either perform more testing of a different nature than that which was originally conducted and/or drive out new certification plans which modify the original certification basis

for the system. This approach is often used when an aircraft design is an improvement (or derivative) of a previously produced and certified aircraft.

The following definitions were used in arriving at the list of New, Significantly Modified Major Structural Components.

New or Significantly Modified Structure - "New" or "significantly modified" structure are structural components that either do not exist on current aircraft of this type, uses a new type of material for primary structure, or otherwise appreciably affects the characteristics of the primary load bearing structure.

Protection designs, whether new or previously used on past derivative designs, shall be subjected to the continued airworthiness analysis proposed by this body of work as part of the design development of the aircraft, since such an evaluation process would not have existed in the early aircraft development program. The presumption for this work is that the aircraft design process has not already been completed.

5.3.4 Indirect Effects Protection General Description for the Case Studies

For induced lightning protection (i.e. indirect effects), special attention is given to protection and verification of flight control systems, displays, and engine control systems. To comply with FAA and JAA requirements for indirect effects lightning protection (FAR 25.1316 and CRI F-03), airplane systems that perform critical and essential functions must be demonstrated to operate safely in the defined lightning environment. The accepted approach to compliance is based on qualification of subsystems in laboratory tests at pre-selected Equipment Transient Design Levels (ETDLs), followed by airplane tests to confirm that Actual Transient Levels (ATLs) experienced by airplane systems, when exposed to lightning, are no greater than the ETDLs minus the appropriate factor of safety. Appendix C and Appendix D (Proprietary Appendices) of the case studies contains a list of all electrical and electronic equipment on the aircraft whose failure would cause or contribute to a failure or function that would affect the continued safe flight and landing of the aircraft or would reduce the capability of the airplane or ability of the crew to cope with adverse operating conditions.

5.3.5 Direct Effect Protection General Description for the Case Studies

For lightning direct effects protection, special attention is given to aircraft strike zones and associate structure within these defined areas [5.53].

The aircraft in these case studies will comply with FAR 25.581 [5.42] and FAR 25.954 [5.43] for lightning direct effects protection. Structure, components, and surfaces will be protected against lightning direct effects in accordance with AC 20-53A, "Protection of Airplane Fuel Systems Against Fuel Vapor Ignition due to Lightning".

To comply with FAA and JAA requirements for the direct effects lightning and fuel tank ignition regulations listed here, aircraft structure exposed to lightning or other ignition sources must be shown to be immune to the defined environment.

1. FAR 25.581 "Lightning Protection"

2. FAR 25.954 "Fuel System Lightning Protection"
3. FAR 25.981 "Fuel Tank Ignition Source Prevention Guidelines"
4. FAR 25.863 "Flammable Fluid Fire Protection"

The basic protection for the aircraft in the case studies is derived from the metallic primary structure; however specific areas such as non-metallic structures and components, the fuel systems, and antenna installations require special attention. The protection of these areas is described in each of the case studies. Figure 5-4 demonstrates the areas of the aircraft where direct effects of lightning strike protection are applied. For purposes of exercising the proposed methodology, certain selected structures will be used as examples to exercise the methodology for both metallic and composite structural protection schemes.

Note that FAR 25.981 [44] also addresses the effects of ignition sources other than lightning. These ignition sources come from fault currents, precipitation static and static energy build up caused by fuel flow across surfaces, for example [5]. Aircraft charging due to p-static results from two atmospheric conditions: 1) the vehicle's presence in a thunderstorm, and 2) the triboelectric charging (frictional) caused by neutral snow, rain, or dust particle bombardment of the vehicle frontal surface. Both charging mechanisms can lead to p-static interference by corona discharges from sharp-edged extremities, streamer discharges on dielectric surfaces, and arc over between electrically isolated or intermittently grounded metallic sections.

The intent of this direct effects protection is to eliminate possible penetration through to fuel cells or damage to structure that can result in a safety event. Direct effects lightning events can result in burning, eroding and blasting of aircraft structure. Direct attachment of lightning to aircraft systems is also a threat requiring design solutions and should be eliminated by modifying the design to provide for appropriate bonding or "shadowing" where an aircraft structure is used to provide for a Faraday Effect "around" the installed equipment or provide adequate structural thickness to avoid lightning penetration to underlying systems equipment.

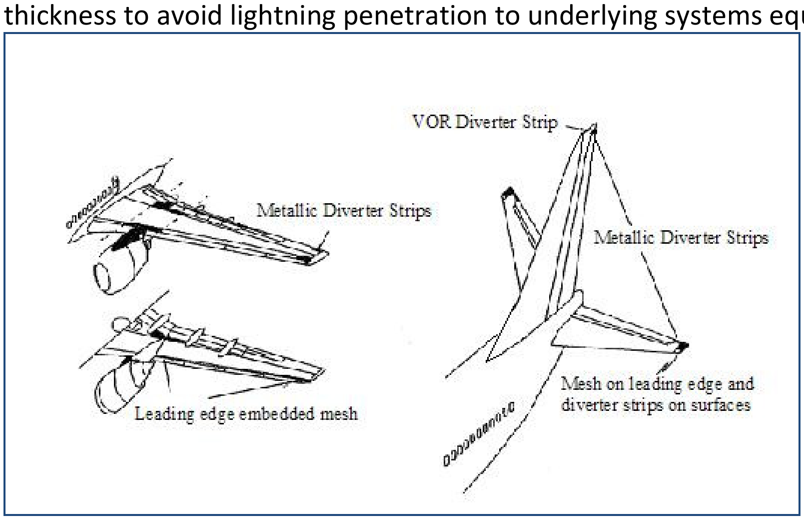


Figure 5-4 Direct Effects Lightning Protection on Engines, Struts, Wings & Empennage

There are two main areas of concentration with regard to protecting the aircraft when from direct lightning effects. The first is wing skin burn through. When a lightning strike attaches to an external structure, all sections of the aircraft must be able to withstand the energy transferred during the strike without burning through the structure. One of the most important parameters is the thickness of the section being struck. This applies to both metal and composite aircraft. Airplanes' with aluminum construction have shown that external structure (wing skins) in excess of 0.08" thickness can withstand lightning strikes with 200 kAmp peak strikes [5.10].

The second area of concentration pertains to the direct attachment of a lightning strike to the head of a structural fastener. It must be shown that given the fastener's location, the fastener can be shown to be struck with lightning and not create an ignition source. Aircraft manufacturers retain experts on this subject which is an entire area of study onto itself. Current practices to obtain additional layers of protection against this threat entails applying a sealant over the base of the fastener to contain any sparking that may occur under fattener installation failure conditions such as an unintentional gap created by an improperly installed fastener.

The aircraft in the case studies uses structural design approaches to prevent direct lightning attachment to underlying systems and their associated components and to prevent significant (in this case significant is referred to as damage that would affect the continued safe flight and landing of the aircraft) structural damage to control surfaces and exterior skins are as follows:

1. Application of a conductive coating (expanded aluminum foil) over composite skins covering equipment and wiring in lightning strike zones 1 and 2.
2. Application of diverter strips or aluminum picture frame to prevent puncture to underlying equipment and minimize damage to composite structure in lightning strike zones 1 and 2.
3. Bonding and grounding or earthing of exterior skins and control surfaces to primary structure using controlled methods in all lightning strike zones.
4. Inherent protection from surrounding metal or conductive composite exterior skins and structure in all lightning strike zones.
5. Location within a zone 3 lightning strike area verified by no history of significant damage to control surfaces, exterior skins or direct lightning attachment to underlying equipment for the aircraft.

For lightning protection of structural designs the FAR 25.981 regulation [5.42] requires the following:

1. The airplane must be protected against catastrophic effects from lightning.
2. For metallic components, compliance with paragraph (a) of this section may be shown by:
    (1) Bonding the components properly to the airframe; or
    (2) Designing the components so that a strike will not endanger the airplane.
3. For nonmetallic components, compliance with paragraph (a) of this section may be shown by:
    (1) Designing the components to minimize the effect of a strike; or

(2) Incorporating acceptable means of diverting the resulting electrical current so as not to endanger the airplane.

The aircraft in the case studies uses fuel system designs that provide protection against sparking and arcing associated with a lightning event and/or electrostatic charge dissipation associated with fluids in motion within the fuel tank system. The design goal is achieved using the following design approaches:

1. Bonding and grounding provisions for fuel tank penetrations, fuel tank access doors, plumbing and equipment within the fuel tank area and fuel tubing outside the tank.
2. Prevention of direct lightning attachment to fuel equipment, wiring and plumbing outside of the fuel tank within lightning strike zones 1 and 2.
3. Prevention of hot spot ignition within the fuel tank area.
4. Inherent protection from surrounding structure.
5. Location in a zone 3 lightning strike area and no history of direct lightning attachment to specific fuel components.

For lightning protection designs for fuel systems, the FAR 25.954 regulation [5.43] requires the following:

The fuel system must be designed and arranged to prevent the ignition of fuel vapor within the system by:

(1) Direct lightning strikes to areas having a high probability of stroke attachment
(2) Swept lightning strokes to areas where swept strokes are highly probable; and
(3) Corona and streamering at fuel vent outlets.

5.3.6 Ignition of Flammable Fluids

These case studies will take into account the presence of flammable fluids as a threat to continued airworthiness. In locations where flammable fluids may be present, a rating will be provided in the environmental threats rating sheet for the presence of flammable fluids. This rating is used to assess the protection design in its installed environment. For the aircraft used in these case studies, precautions have been taken to safeguard against the ignition of flammable fluids in accordance with FAR 25.863 titled: “Flammable Fluid Fire Protection” [5.45]. Prior to the emergence of Special Federal Aviation Regulation 88 (SFAR 88), designers assumed that fuel tanks perform similar to a Faraday Cage minimizing the induction of electromagnetic fields onto components within the fuel tank. [5.13]

Aircraft Fire Zone

A fire zone is an area where a fire is possible. In a fire zone, an ignition source or a flammable liquid or a flammable vapor is present during normal operation, and the possibility of having both an ignition source and a flammable liquid or vapor present after a single failure cannot be absolutely excluded. Fire zones must be equipped with fire detection, containment or control, and extinguishing equipment.

The following special design requirements apply to fire zones:

A. All electrical equipment in the fire zone shall be explosion proof when tested according to Procedure II of MIL-STD-810B, Method 511 [5.39] or if not normally exposed to a spark source, shall receive special treatment, such as potting or mounting in a vapor-tight area or within a sealed flame barrier or shall be designed so that it will not produce an arc or spark within a fire zone having an energy level greater than a specified number of joules (value can be found in the reserved proprietary version of these case studies).
B. All electrical terminations shall be protected to prevent arcing or sparking. (FAR 25.863) [5.45]
C. Firewall connectors and the passage of all wiring through the firewall shall be as fireproof as the firewall itself: capable of withstanding 2000°F for 15 minutes. (FAR 25.1203) [5.46]
D. For all critical safety circuits, fire resistant wiring shall be used in the fire zone. All other circuits in the fire zone shall use high temperature wire.

Aircraft Flammable Zone

Flammable zones are areas where flammable liquids or vapors are present during normal operation.

The following special design requirements are applicable in flammable zones:
A. As installed, all electrical equipment in the flammable zone shall have all electrical equipment, wiring, and terminations housed in a case that is explosion proof when tested according to Procedure II of MIL-STD-810B, Method 511 [5.39]. The integrity of the explosion proof case shall be maintained under any condition of equipment or system malfunction or shall be designed so that it will not produce an arc or spark within a flammable zone with an energy level greater than a specified number of joules (value can be found in the reserved proprietary withheld version of these case studies). This requirement must be met during both normal operation and when there is a failure in any part of the circuit, either inside or outside of the flammable zone or shall be hermetically sealed.
B. The surface temperature of equipment, components, and wiring that is exposed to flammable fluids or vapors shall not exceed 390°F during normal operation or under failure conditions.
C. Equipment in flammable zones shall be installed with dual grounds.

Aircraft Flammable Leakage Zone (Combustible Zone)

Flammable leakage zones are areas in the unpressurized portions of the airplane where flammable liquid or vapor can be expected to be present because of a single failure or from leakage during normal operation.

The following design requirements are applicable in flammable leakage zones:
A. As installed, all electrical equipment in the flammable leakage zone shall be explosion proof when tested according to Procedure II of MIL-STD-810B, Method 511 [5.39] or if not normally a spark source, shall receive special treatment, such as potting or mounting in a vapor-tight area or within a sealed flame barrier, or shall be designed so that it will not produce an arc or spark within a flammable

leakage zone with an energy level greater than a specified number of Joules. (FAR 25.863 (b) (3)) [5.45]

B. All electrical terminations shall be protected to prevent arcing sparking. (FAR 25.863 (b) (3)) [5.45]
C. The equipment surface temperature and wiring shall not exceed 450°F during normal operation or under failure conditions. (FAR 25.863 (b) (3)) [5.45]
D. Equipment in flammable leakage zones shall be installed with dual grounds.

Aircraft Ignition Zone

Ignition zones are portions of the airplane zone from which flammable liquids and vapors shall be excluded because ignition sources may be present during normal operation. Wire looms shall be designed for temperature resistance in accordance to the zone in which they are installed. The following wire loom grades are used as a guide for determining appropriate design decision making when selecting wire looms to install within specified locations.

5.3.7 Temperature

To minimize the degradation of parts and materials, both maximum ambient and loom operating temperature is considered when selecting electrical components. The maximum ambient temperature varies throughout the aircraft.

Maximum Operating Temperature

Electrical components and materials have a maximum temperature rating. This rating must exceed the wire loom continuous operating temperature, which includes the airplane ambient temperature and the loom operating temperature.

Localized Temperatures

Localized continuous temperatures must be considered when selecting electrical components and materials. A wire loom assembly installed in close proximity to the following components may be subjected to temperatures that are significantly higher than the designated ambient temperature of an environmental area.

- Bleed air ducts
- High power electrical equipment
- Electronic boxes
- Lights
- Air conditioning packs and ducts
- Other heat sources

Excursion Temperatures

A wiring installation or assembly may be subjected to high temperatures for short periods of time, a condition referred to as an excursion temperature. (An example is an oxygen generator.) For such installations, component and material selections must consider the excursion temperature. Approval by the Airworthiness Representative (AR) may be required if the excursion temperature exceeds the maximum rating of the component or material.

Wire Loom Temperature Grade

The design system uses wire loom temperature grades to indicate the rating of the processing materials (labels, ties, sleeves, and so forth) used in the wire loom assembly and as general parameters for the selection of some types of parts.

Wire loom temperature grades are designated by letters as shown in Table 5-1. Each letter grade corresponds to a continuous temperature rating for the wire loom processing materials only. The wire loom temperature grade is not the maximum temperature rating of the wire, cable, and other the components used in the wire loom assembly. Refer to the wire, cable, and component detail drawings and specifications for the ratings of these materials.

Wire Loom Temperature Grades Table included in Proprietary Appendix.

Wire Loom Temperature Grades	
Grade	**Allowable Temp (°C)**
A	Proprietary data
B	Proprietary data
C	Proprietary data
D	Proprietary data

Table 5-1 Wire Loom Temperature Grades

5.3.8 Vibration

For the design and installation of wire loom assemblies, areas of the airplane are classified into three vibration categories as shown in Table 5-2.

Category 1: Locations on aircraft included in Proprietary Appendix
Category 2: Locations on aircraft included in Proprietary Appendix
Category 3: Locations on aircraft included in Proprietary Appendix

Each category corresponds to the severity of the vibration that occurs in the indicated area of the aircraft. The part selection tables either directly or indirectly account for these vibration levels. The vibration category also governs the selection and spacing of wire loom clamps and ties.

The following design requirements apply to the vibration categories:

Category	Requirement
1	Wire loom tie spacing requirements included in Proprietary Appendix
2	Wire loom tie spacing requirements included in Proprietary Appendix
3	Wire loom tie spacing requirements included in Proprietary Appendix

Table 5-2 Vibration Category Design Requirements

5.3.9 Fluid and Moisture Protection

Numerous fluids throughout the aircraft can contribute to the degradation of components and materials that come into contact with those fluids. In addition, moisture protection zones in the pressurized cabin can be subjected to large amounts of water during landing cycles.

Fluid Exposure

Fluids that may affect part selection and installation include the following:

- Hydraulic fluid
- Jet fuel
- Lubricating oils
- Alkaline detergents

With the exception of hydraulic fluid and jet fuel, the numerous fluids used on the airplane are tolerated by most components and materials. Tolerance to specific fluids may be acquired by the design engineer responsible for the component.

For example, hydraulic fluid and jet fuel can degrade nonmetallic materials such as connector grommets, clamp cushions, and rubber seals. Components and materials classified for use in unpressurized areas typically provide some resistance to hydraulic fluid and jet fuel. Prolonged exposure to hydraulic fluid may require specialized components and materials that provide improved resistance to this fluid. Wire looms are classified as to whether or not they are exposed to hydraulic fluids. This designation ensures that the materials used in wire loom fabrication are resistant to hydraulic fluids.

Moisture Protection Aircraft Zones

Near the airplane's doors, warm humid air can condense on the cold structure, and then moisture can drain through the insulation blankets onto electrical components and wire looms. Moisture and associated contaminants may intrude into non-sealed electrical components and cause internal shorting between circuits.

Equipment supplied by the buyer presents a special concern when the equipment contains connectors that do not have seals to mitigate water ingress into the connector interface with other equipment on the aircraft. In such cases, the designer must know the design limits of the connector and use methods to prevent the ingress of moisture into the connector. Such methods for mitigating moisture may include the following:

- Drip loops (wire looms with intentional loops to wick moisture away)
- Drip shields (covers over critical wire connections)
- Circuit types and layouts.
- Protective means to prevent water from dripping through insulation blankets such as water egress paths.

Special Wind and Moisture Protection Zones

These areas are locations on the aircraft where wire looms are frequently or continuously exposed to moisture and most airplane fluids.

Fuselage Top View

Proprietary Graphic Retained

Legend	Airplane Area	Fire Protection Zone	Wire Loom Temperature Grade	Vibration Level	Hydraulic Fluids
	Unpressurized Area: Radome	Ignition	B	2	No
	Pressurized Area: Cabin	Ignition	A	1	No
	Pressurized Area: Cargo area, Electronic Equipment Compartments & Equipment bays	Ignition	A	1	No
	Unpressurized Area: Wind area, wheel wells	Flammable Leakage	B	2	Yes
	Unpressurized Area: Environmental Control System (ECS) bay	Flammable Leakage	B	2	Yes
	Unpressurized Area: Center fuel tank	Flammable	B	2	Yes
	Unpressurized Area: Wind area, wheel wells	Flammable Leakage	B	2	Yes

Table 5-3 Airplane Environmental Attributes associated with aircraft fuselage locations.

Wing Top View

Proprietary Graphic Retained

Legend	Airplane Area	Fire Protection Zone	Wire Loom Temperature Grade	Vibration Level	Hydraulic Fluids
	Unpressurized Area: Wing leading edge	Flammable Leakage	B	2	Yes
	Unpressurized Area: Wing to body fairing	Flammable Leakage	B	2	Yes
	Unpressurized Area: Landing lights	Ignition	B	2	No
	Unpressurized Area: Wing fuel tank	Flammable	B	2	Yes
	Unpressurized Area: Wind area, trailing edge	Flammable Leakage	B	2	Yes
	Unpressurized Area: Wingtip lights	Ignition	B	2	No
	Unpressurized Area: Strut	Flammable Leakage	B	3	Yes

Table 5-4 Airplane Environmental Attributes associated with the Wing locations

Tail Top View

Proprietary Graphic Retained

Legend	Airplane Area	Fire Protection Zone	Wire Loom Temperature Grade	Vibration Level	Hydraulic Fluids
	Unpressurized Area: Empennage	Flammable Leakage	B	2	Yes
	Unpressurized Area: Auxiliary Power Unit (APU)	Fire	B	3	Yes
	Unpressurized Area: Fuselage Aft of Pressure bulkhead	Flammable Leakage	B	2	Yes

Table 5-5 Airplane Environmental Attributes associated with the Tail locations

Fuselage Side View

Proprietary Graphic Retained

Engine Area and Landing Gear

Proprietary Graphic Retained

Legend	Airplane Area	Fire Protection Zone	Wire Loom Temperature Grade	Vibration Level	Hydraulic Fluids
	Unpressurized Area: Engine Core	Fire	D	3	Yes
	Unpressurized Area: Engine fan compartment	Flammable Leakage	B	3	Yes

Table 5-6 Airplane Environmental Attributes associated with the Engine Area and Landing Gear

Tail—Side View

Proprietary Graphic Retained

Legend	Airplane Area	Fire Protection Zone	Wire Loom Temperature Grade	Vibration Level	Hydraulic Fluids
	Unpressurized Area: Rudder	Flammable Leakage	B	2	Yes

Table 5-7 Airplane Environmental Attributes associated with the Tail Side View

5.4 Design Approach using "As Installed" Threats

For the design of electrical and mechanical components within lightning strike zones, care is taken to ensure that the designs are robust enough to withstand normal operational wear while at the same time, maintaining availability against the adverse effects of lightning. Use of a comprehensive method for design criteria goes beyond establishing design requirements and into the realm of practical applications. Qualification testing may provide some insight as to the ability of any component to withstand environmental threats such as vibration, moisture and temperature cycling however; it is often difficult to create such combined environmental threats while also performing the intended function under test.

Aircraft designs are certified for appropriate application of requirements, design and qualification. Current industry practices do not require qualification tests to substantiate component aging trends and compounded environmental threats. The challenge for system designers is to find useful information to support the proposed methodology from the qualification test results as currently implemented. A process by which one might develop quantitative data from qualification testing is not defined. It is generally accepted that qualification testing does not directly represent the installed environment for components over time. Without a model that can process qualification test results into data that represents combined threats within installed environments one cannot predict component performance in-service, and the association with the component performance effects on EMC qualification margins. To develop this process requires significant resources from those responsible for qualification of components. If the quantitative data was made available during the qualification testing, designers would then perform an in-depth system by system analysis to establish levels of margin.

Past techniques used to certify aircraft systems to specified lightning indirect effects require application of continued airworthiness compliance criteria [5.19]. Without adequate continued airworthiness criteria during the design phase, many aircraft system design firms have no choice but to establish continued airworthiness instructions after the design is firm. This approach to aircraft design is typical today. The proposal made by this work recommends a more integrated approach to design that uses test data in a progressive manner to substantiate continued airworthiness designs. One early design criteria that can be addressed as part of the continued airworthiness evaluation might be a galvanic assessment of components that rely on good earthing systems and techniques to protect against the potentially adverse effects of lightning. Galvanic assessments can be done as part of the continued airworthiness evaluation but are typically initiated after design decisions are completed. For electromagnetic compatibility, qualification methods exist for establishment of transient level “margin” that accounts for uncertainties in verification methods [5.20]. Once aircraft installed system threat levels are determined – by test or analysis – they are extrapolated to external threat waveforms and levels. After this is completed, these threat levels are then compared and used to demonstrate “margin” [5.19]. As discussed in Chapter 2, these design margins have been found to be inadequate as design criteria for continued airworthiness and are used to establish the initial certification basis for the systems.

It is apparent within the industry that component design margins cannot be used to substantiate continued airworthiness however; use of test results may be insightful towards assessing performance in service. An analysis of test data may be reliant on sampled test points and worst case applications of the established criteria that would modify the current use of margins. The challenge is to predict component aging trends using qualification data as it is currently collected. Degradation trends may be linear, non-linear, or remain unchanged depending on the environmental threats presented by the installed environment. As components are tested for general performance under the environmental threats created in the laboratory, it is necessary to take results of these tests and evaluate each design under a more specific installed environment application. This is necessary as some components are installed outside the pressure vessel and some are installed inside the pressure vessel while the same laboratory test may be used for both applications. Further complicating use of unaltered qualification test results is the interaction of components that make up the earthing plan for a system such as earthing jumpers, wire loom shields and connector material and finish. One component of a shielding ‘system’ can simply eliminate the margin established in test.

Though testing of equipment and lightning protection components is an important part of the airworthiness equation, use of any test results to conclude continued airworthiness is in its infancy. The proposed methodology for determining continued airworthiness through use of the engineering assessments forms presented in this thesis is a beginning point for taking this design process one step further. Future investigations and modeling of in-service degradation can enhance the methodology proposed in this work.

5.5 Path Through to Certification

The following design processes in Figure 5-5 are presented in relation to each other in order to demonstrate the path to certification drawing attention to how the continued airworthiness methodology affects the design process. Most often, design processes such as the ones identified in the Figure 5-5 are performed in parallel and associate across different design disciplines within the larger design process. For this reason, many of the design processes feed back into each other as solutions are identified and proposed. Electromagnetic protection design requires calculations, estimates, and testing to determine an optimum protection design. Aircraft manufacturers have implemented different solutions to the integration of these design processes. For the purpose of these case studies, the integration of the methodology will be accomplished by use of examples and are demonstrated in principle through these examples. The continued airworthiness of lightning protection is an engineering process that requires certain physical properties associated with the lightning protection component to be determined in order to perform the proper evaluation. Compatibility of materials and threats associated with the installed environment should be collected along with other design data to exercise the methodology as demonstrated by these case studies.

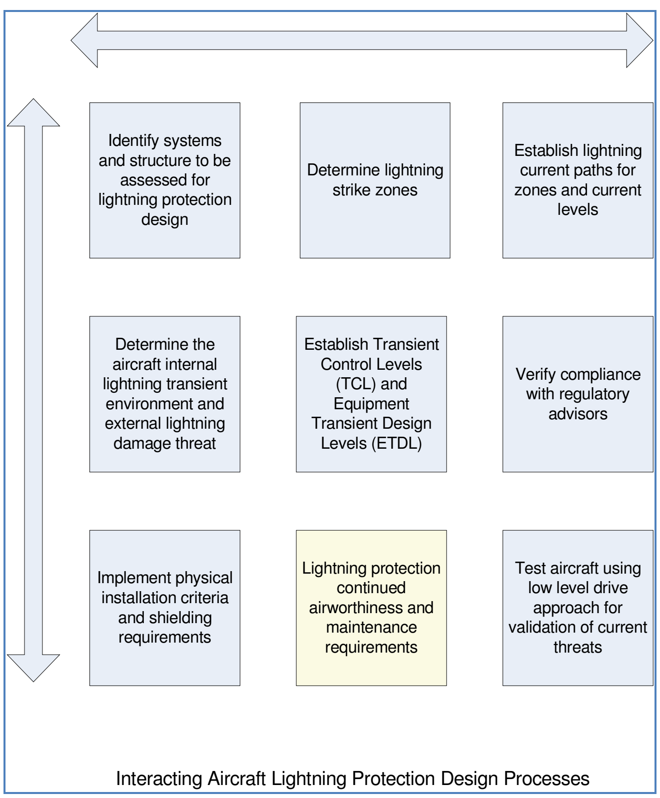


Figure 5-5 Route through Design Process

5.6 Possible Routes through Design Process

As the design process moves through Conceptual, Preliminary and Detailed Design stages, several possible requirements for design evaluations are generated by the interacting design processes shown in Figure 5-6.

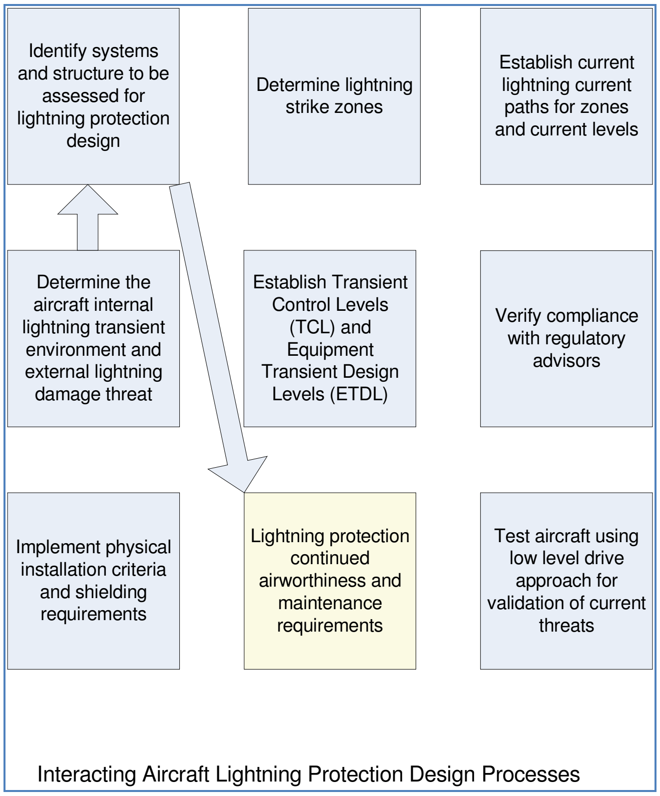


Figure 5-6 Lightning Threat Determination Resulting In Protection Designs

An example of one possible route through the design process could be shown in Figure 5-6 where lightning threat determinations result in lightning protection designs that require a continued airworthiness evaluation. As shown in Figure 5-6, once the lightning threat is determined, the electromagnetic engineering team may provide options for appropriate protection of the systems and structure within the determined lightning threat location. As these options are evaluated in the laboratory and developmental testing scenarios for effectiveness in protecting the aircraft is concluded, the continued airworthiness "Engineering L/HIRF Protective Device Assessment Sheet" developed as an implementation of a new concept for this work can be completed with findings that are relevant to the designs under test. This will provide the selection team with additional information on the long term performance of the protection schemes to optimize a better design alternative.

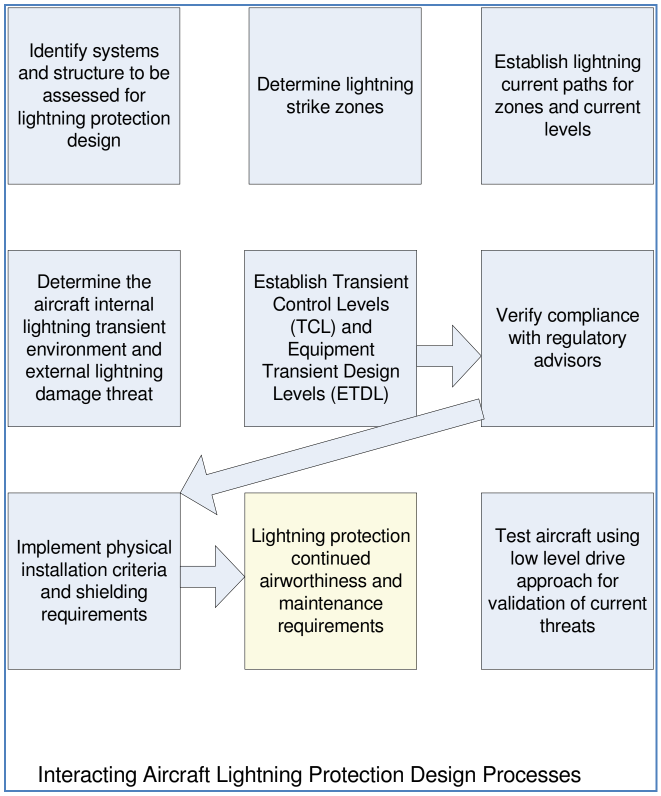


Figure 5-7 Lightning Current Levels Resulting in Loom Shielding Design

Another possible route through the design process could be as shown in Figure 5-7 where avionics boxes are designed to sustain continued safe operation through lightning transient events that comply with regulatory requirements governing the design selection [5.2] and resulting in a specific selection of loom shields. These loom shields and associated connectors plugs and connector back shells make up a significant portion of the lightning indirect effects protection. Note that protection within avionic equipment also provides protection from indirect effects. Once the shield designs are selected, the process of evaluating continued airworthiness effectiveness using the "Engineering L/HIRF Protective Device Assessment Sheet" can begin. Assessments of qualification testing and laboratory testing for new shield and connector types will result in appropriate feedback into the design process necessary to result in an optimized lightning in-direct effect protection design.

In Figure 5-8, the route to certification describes the design process where the aircraft lightning zones and threats have been defined, the aircraft design has been established and coordinated with the regulators within preliminary certification plans and the first completed aircraft is tested using a simulated Low Level Direct Drive test using appropriate current waveforms to determine the aircraft lightning protection performance and support certification. The approach to compliance is based on qualification of subsystems in laboratory tests at preselected levels, followed by airplane tests to confirm that actual levels experienced by airplane systems when exposed to lightning are no greater than laboratory test levels. If findings of the these low level simulated lightning tests show that additional shielding may be required for a certain part of the aircraft for example, then the continued airworthiness of the additional protection will require assessment using the “Engineering L/HIRF Protective Device Assessment Sheet”. Documenting the equipment wiring voltages and currents, and airplane skin currents that result from the tests immediately after acquisition of the data will allow the comparison of the airplane level test data to the equipment qualification test data. As part of the path to certification, these comparisons are summarized and evaluated to ensure adequate protection is provided to meet the required qualification levels set by the early design. Determining the lightning paths and current levels assists design engineers to create a comparison to qualification levels. This is provided to the certifying office for confirmation of the appropriate lightning design protection.

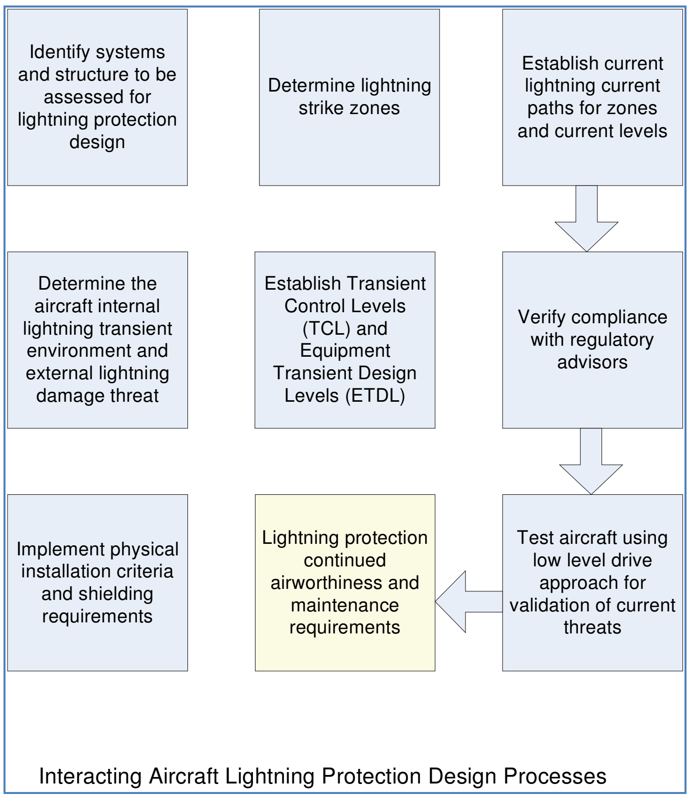


Figure 5-8 Aircraft Testing Resulting in Modifications to L/HIRF Protection

During the early part of the design development process, as the aircraft shape and lightning threats are defined, systems and structures that are affected by lightning threats are identified. The structural components in lightning threat zones may require protection on such structural elements as: wing tips, rudder trailing edges and other structural components listed in these case studies. As these structural components are identified, the physical implementation is also detailed such as required sealants that protect interfaces between the protection and the structure, fasteners and structural assembly components that become part of the critical current carrying path. Figure 5-9 emphasizes the importance of the physical characteristics of lightning protection installations. Structural protection component installation details are transmitted to the continued airworthiness evaluation process as part of the design methodology proposed in this work. Also part of this path to certification is the determination of shielding on critical and essential aircraft system looms. Part of this shielding design may be earthing cables or other earthing elements associated with the loom connectors or equipment earthing techniques such as connector shield terminations. Specific interfaces such as receptacle to equipment surface galvanic compatibility or earthing cables attaching hardware galvanic interfaces are processed through the "Engineering L/HIRF Protective Device Assessment Sheet" to determine appropriate protection selection.

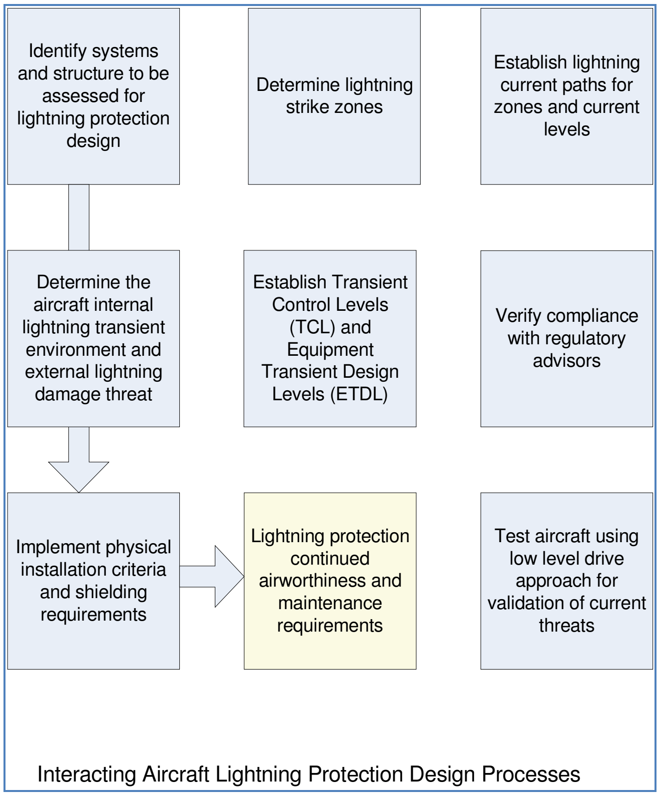


Figure 5-9 Significant Structural and Systems Protection Physical Characteristics

5.6.1 Lightning Protection Design Features and Aircraft Installations

Understanding the lightning strike zones for an aircraft is an important first step in the aircraft lightning protection design process. Figure 5-10 provides the lightning zones for the large transport category aircraft in these case studies (the actual aircraft zoning diagram is included in the Proprietary Appendix of this thesis to protect the proprietary nature of the information. As an aircraft designer estimates the strike impact and distribution, protection against estimated lightning effects is also determined. In Chapter 2 of this thesis is was stated that most direct lightning strike attachments will be to the nose, wing tip, vertical stabilizer, engine inlets and nacelles, horizontal stabilizer and other installations within lightning Zone 1. Historical data and testing show that lightning strikes are more likely to attach in these parts of the aircraft. Areas where the initial strike is less likely to occur are the drain masts, pilot probes, blade antennas, the extended ends of leading edge slats, trailing edge flap track fairing tips and the landing gear. Figure 5-10 details the three lightning zones and the probability of a strike in each of these aircraft locations.

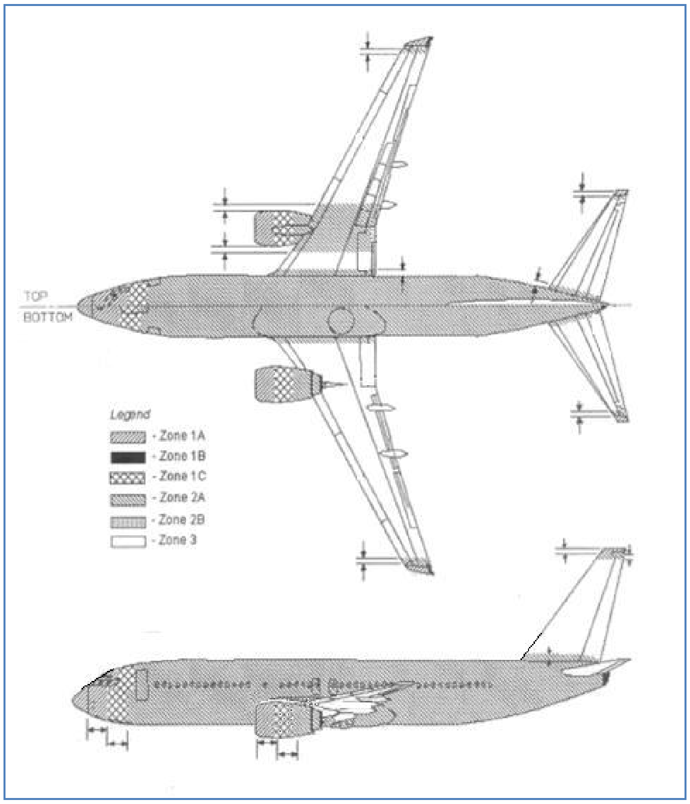


Figure 5-10 Aircraft Lightning Strike Zones Probability

5.6.2 Effects of Lightning Protection Design on Aircraft Operations

As discussed in previous sections of this thesis, lightning strikes can cause two types of damage:

- Damage due to "Direct Effects" of lightning
- Damage or operational interrupt due to "In-Direct Effects" of lightning

1. Direct Effects can result in damage at strike location and is described as follows:

a. Metallic surfaces are burned, melted or show signs of metal distortion.
b. Non-metallic surfaces are burned, punctured or delaminated.

Direct damage on metal structures will usually show as small circular melt marks approximately 1/8 inch in diameter. The melt marks can be in a small area along the fuselage while on a trailing edge surface, the melt marks can be along a larger surface area. Holes in the structure with a 1/4 inch diameter or greater are possible if a high intensity lightning strike occurs on the aircraft structure. In these areas, additional protection may be provided as part of the protection features as discussed within these case studies. Other signs of direct damage might be burned or discolored skins and fasteners. Cases have occurred where ferrous components have become strongly magnetic after a lightning strike due to heavy lightning currents that are nearby.

2. Indirect Effects can result in system upset and is described as follows:

Indirect effects are identified as damaged or upset electrical/electronic systems equipment, wire shielding and shield terminations. This is caused by large electrical transients on the aircraft wiring. High intensity lightning strikes can cause problems to the electrical/electronic equipment. While electrical systems are generally protected by surrounding structure from a possibility of direct lightning strike attachment to electrical/electronic wires and cables, damage can occur to equipment from induced currents. A high intensity lightning strike can produce electromagnetic fields within the unpressurized areas that are large enough to cause possible damage to the electrical system components. Specifically, problems to components which are located external to the pressurized fuselage may experience greater lightning threats due to the installed location. Wire shielding may also be disturbed or degraded during the life of the aircraft. The methodology created within this body of work was created to ensure the long term availability of lightning protection for both direct and indirect lightning strike threats through the development and implementation of a design methodology dedicated to the continued airworthiness of lightning protection.

Lightning indirect effects are difficult to measure during aircraft operation. Often during a lightning strike event, a pilot may notice static on the communication radios but little else in terms of flight equipment malfunction. At other times the effect can be quite dramatic including loud noise, the glow from corona effects on the radome and a bright flash that sometimes can even temporarily blind the pilot. After a lightning strike is identified by a pilot, a decision is made in real time to either continue the flight or return to the base in which the aircraft was dispatched for an inspection of potential damage caused by the strike. Sometimes the decision to return to the airport or continue on to the destination is made based on the ability of the airline to do a proper inspection with the proper support and tools required to repair or inspect damage caused by lightning at the departure point. At times airlines may direct the airplane to continue on with the flight as planned to ensure that the proper equipment is available for conducting the post-lightning strike inspection.

5.6.2.1 Instructions for Inspections of Lightning Protection Designs

Lightning strike inspections are conducted after a known lightning strike event to determine what repairs may be needed before dispatching the aircraft. In general, the procedure for conducting the lightning strike conditional inspection has two tasks that are typical of all lightning strike inspections.

1. Examination of the external and internal areas of the aircraft to identify lightning strike damage.
2. Operational checks of communication and navigation systems.

5.6.2.2 General Guidance for Post Lightning Strike Inspections

Examination of <u>external and internal</u> areas for lightning strike damage:

The following guidance is typical for accommodating the Instructions for Continued Airworthiness in an aircraft maintenance manual. The purpose of including this guidance within these case studies is to provide the framework for what is considered important to the continued airworthiness of airplane systems and structures for maintaining appropriate and safe flying configuration. Although it is not suggested that the methodology proposed use these instructions as a guide for defining the most critical lightning protection components, it is important to understand the operational aspects of aircraft and impacts to the operations when lightning protection or aircraft systems and structures are affected after a strike.

After the airplane is struck by lightning, a general inspection of the airplane is done to find the areas of the strike. There are always at least two strike points at different areas of the airplane surface; an entrance point, and exit point. A careful inspection of the strike area is done to find the type and amount of damage which has occurred. As discussed in this chapter regarding the presence of the Faraday Cage effect, the basic protection for fuel and for critical electronic systems is the metal fuselage and wing structure. Necessary protection is also supplied for the non-metal structure by aluminum mesh (the rudder is typically protected with metallic strips in a square configuration on top of the control surface). Technicians performing the inspection need to remain aware of these types of protection features in order to perform a thorough evaluation of the damage during the inspection. The external structure prevents fuel ignition and electrical/electronic system damage. Critical electronic systems also rely on wire shields and proper shield terminations for indirect effects protection. When lightning initially strikes on the forward fuselage or engine nacelles, it will move aft over the fuselage surface or over the wing surface. On the wing surface, the lightning will move aft of the nacelle or aft of the extended ends of the leading edge slats. This is important to know so that inspections can be done that follow the typical path of the lightning strike as it sweeps across the aircraft structure. When lightning initially strikes the aft area of the empennage or wing surface, it will remain until the lightning current stops. This is called “hang-on” and can cause significant damage at the location where the hang-on occurs. Technicians can use Figure 5-10 to assist in determining the likelihood of strike locations on the aircraft and also provide the appropriate focus for the inspection.

The areas that initial lightning strikes will most occur are as follows:
a. nose section and radome
b. engine nacelles
c. wing tips
d. horizontal stabilizer tips and elevator tips
e. vertical fin tip and rudder tip.

The areas that initial lightning strikes do not normally occur are as follows:
a. drain masts
b. pitot probes
c. blade antennas
d. extended ends of leading edge slats
e. trailing edge flap track fairing tips
f. landing gear

Inspect for two types of damage, Direct and In-Direct:
Direct Damage is defined as follows:

- Metallic surfaces are burned, melted or show signs of metal distortion.
- Non-metallic surfaces are burned, punctured or delaminated.

For direct damage, look for damage on metal structures that will usually show as small circular melt marks approximately 1/8 inch in diameter.
NOTE: The melt marks can be in a small area.

a. On a trailing edge surface, the melt marks can be along a larger surface area.
b. Holes with a 1/4 inch diameter or greater are possible if a high intensity lightning strike occurs.
c. Other signs of direct damage might be burned or discolored skins and fasteners.
d. Cases have occurred where ferrous components have become strongly magnetic because of heavy lightning currents that are nearby.

Indirect Damage is defined as follows:

- damaged or upset electrical/electronic systems equipment
- damaged wire shielding and shield terminations.

For indirect damage, look for equipment that does not operate properly. High intensity lightning strikes can cause problems to the electrical/electronic equipment.
NOTE: While the electrical system is protected from a possibility of direct lightning strike to electrical/electronic wires and cables, damage can occur. A high intensity lightning strike can produce electromagnetic fields within the unpressurized areas that are large enough to cause possible damage to the electrical system components.

a. Specifically, problems to components which are located external to the pressurized fuselage.
b. Wire shielding may also be disturbed or degraded.

When evaluating the pilot report, frequently a lightning strike is referred to as a static discharge. This incorrect reference sometimes causes confusion about the purpose of static dischargers (small rod devices) installed on the tips and trailing edges of airfoils. These devices do not prevent the lightning strikes on the airplane. They can however, be severely damaged during a lightning strike and should be included in the inspection. The primary function of the static dischargers is to bleed off the static charge on the airplane during operation. This is to prevent static radio interference in the airplane avionics receivers (e.g. VHF Communication, ADF, and VOR). The static dischargers are frequently hit and damaged by lightning. Some of them are installed at a specified point as protection to a light or other system component. This is an added function beyond their normal function of static bleed off.

To perform the evaluation of the aircraft after a lightning strike has been reported, do the following;

A. Lightning Strike Inspection- Examine the Airplane External Surfaces

1. Examine the areas where the lightning strike occurred for signs of damage.
    a. Examine the Zone 1 surface for signs of a lightning strike (Figure 5-10).
        i. Examine the external surfaces of the nose radome.
            a) Look at non-metallic structure for burns, punctures, and holes.

        ii. If damage is found on the external surface of the nose radome, examine the internal surfaces of the nose radome.
            a) Look at non-metallic structure for burns, punctures, and holes.
        iii. Examine the metal structure for holes or pits.
            a) Look for burned or unusual colored skin or rivets.
        iv. Examine the external surfaces of the non-metallic components.
            a) Look for discolored paint and burned, punctured, or delaminated skin plies.
2. Repair or seal the damaged areas.
3. Examine the Zone 2 surface for signs of a lightning strike (Figure 5-10)
    a. Examine the Angle of Attack (AOA) sensors.
    b. Examine the pitot probes, static ports, and the areas near for damage. Look for burns, punctures, discolored paint, and general skin distortion.
        i. If damage is found, refer to the structural repair manual for appropriate repair instruction.
    c. Examine the metal structure for holes or pits.
        i. Look for burned or discolored skin or rivets
    d. Examine external surfaces of composite honeycomb components.
        i. Look for discolored paint, burned, punctured, or delaminated skin.
4. Repair or seal the damaged areas.
5. If the entrance and exit points are not found during the examination of Zones 1 and 2 areas, examine Zone 3 (Figure 5-10) surface areas for signs of lightning strike damage.
    a. Do the examination that follows:
        i. Examine the external surfaces carefully to find the entrance and exit points of lightning strike.
        ii. Examine areas where one surface stops and another surface starts.
        iii. Examine the metallic structure for holes, pits, burned or discolored skin and rivets.
        iv. Examine the external surfaces of the composite components for discolored paint, burned, punctured, or delaminated skin plies.
        v. You need to use instrumental Non-Destructive Inspection (NDI) methods or tap tests to find composite structure damage that you cannot see. Damage you cannot see, such as delamination, can extend to the area you can see. Delamination can be detected by instrumental NDI methods or by a tap test. For a tap test, use a solid metal disk and tap the area adjacent to the damaged area lightly. If there is delamination, you will hear a sound that is different than the sound of a solid bonded area. Refer to the appropriate Nondestructive Test Manual.
6. Examine the composite structure around the area where a lightning strike may have occurred.
    a. Do the NDI procedures or the tap test.
7. Repair or seal the damaged areas.
8. Examine all of the external lights.
    a. If you find damaged lights, check the items that follow:
        i. the wires at the damaged light

        ii. the wires from the light that connect the light to the circuit breaker.

9. Do a test of the lights that follow:
    a. Do this task: Anti-Collision Lights - Operational Test,
    b. Do this task: Emergency Lights - Operational Test
10. Examine the flight controls that follow:
    a. If the rudder shows signs of a lightning strike, examine these items:
        i. The surface hinges
        ii. The bearings
        iii. The bonding
    b. If the elevators show signs of a lightning strike, examine these items:
        i. The surface hinges
        ii. The bearings
        iii. The bonding
    c. If the ailerons show signs of a lightning strike, examine these items:
        i. The surface hinges
        ii. The bearings
        iii. The bonding
    d. If no damage is found, do a basic operational check of the flight controls:
        i. If the flight controls operate correctly after you do these steps, no more inspections are necessary.
        ii. Move rudder, control wheel and control column in both directions.
        iii. Make sure that there is full travel and the flight controls move freely. Hold the nose wheel during the rudder check to prevent nose wheel movement. You can hold the nose wheel if you put in the steering lockout pin or remove the torsion link pin.
11. Do a functional test of the rudder system if it did not operate correctly during the operational check of the flight controls steps above.
12. Do a functional test of the elevator system if it did not operate correctly in the test of the flight controls, as performed in the steps above.
13. Do a functional test of the ailerons if they did not operate correctly in the tests the flight controls steps above.
14. If the wingtips show signs of a lightning strike, examine the wingtips carefully.
    a. Also look at the fuel vent outlet and surge tanks for signs of damage.
15. If the winglets show signs of a lightning strike, do a close visual examination on the winglets.

B. Lightning Strike Inspection - Examine the Static Dischargers

1. Do the inspections that follow:
    a. Ensure static dischargers are attached and not broken.
    b. Examine the dischargers for the following:
        i. Burns
        ii. Rough coating
        iii. Pitted metal discharger retainers
    c. Examine the dischargers for the following:
        i. Broken pins
        ii. Bent pins (Bent pins must be made straight)
        iii. Blunted tungsten pins
    d. Look at the discharger for the following:

            i. Erosion of the discharger coating
    2. Do a resistance test if there is a damaged static discharger

C. Lightning Strike Inspection - Examine External Wire Shields

1. If there is not an identified entrance or exit point for the lightning strike, a visual check is not required. If there is no shield termination(s) in the area of an entrance and/or exit point, then no further visual check is required.
2. In the area of the entrance and exit, check damage to shield terminations
3. If damage is found at shield termination(s), check the wire loom run
4. Repair any damage found.

D. Lightning Strike Inspection - Airplane Internal Test

1. If a lightning strike caused a system malfunction, do a full test of the defective system.
    a. Use the applicable instructions for that system.
2. Do a check of the standby magnetic compass system only if the flight crew found a deviation that is more than is permitted
3. Make sure that the fuel quantity system is accurate.
    a. Do the operational test for the FQIS type on your airplane
    b. If the FQIS test shows any problems, check the Fuel Quantity Indicating System (FQIS) with the Fuel Measuring Sticks
4. This may be done as an alternative to above.
    a. The center tank must be emptied (by transferring fuel to the left and right tanks), and the empty indication would be verified to be correct.
    b. The fuel from the left and right tanks will transfer to the center tank.
    c. The left and right tank empty indication would be verified.
    d. Fuel would be added as necessary to fill the center tank to capacity, and the indication would be verified.
    e. Fuel would be transferred to fill the left tank to capacity, and the indication would be verified.
    f. Fuel would be transferred to fill the right tank to capacity, and the indication would be verified.

After a lightning strike event, the operating airline uses both written inspection procedures and good judgment to determine the amount of inspection that is appropriate. The number of inspections and nature of the inspection after a lightning strike to the airplane is determined by evaluation of the flight crew information and the airplane condition after the incident. For example, if all the NAV/COM systems are exercised by the flight crew in flight after the lightning strike and no anomalies are found, then checks to the exercised systems would not normally be required. For systems not exercised by the flight crew in flight or systems where anomalies were found during the lightning strike internal and external inspection, additional checks to that system may be required once the aircraft reaches the ground. In addition, even if a system was exercised in flight after the lightning strike and no anomalies were found, but subsequent inspections showed lightning damage near that system antenna, additional checks of that system will be required. The level of the inspections and operation tests will come from flight crew information and the airplane conditions during, and after the incident.

From this point in the post-lightning strike inspection, a non-routine test may be required depending on the findings on the inspections and tests performed. It is not necessary to examine the coaxial cables and the connectors if the:
(a) Radio system had no problems during and after the incident, and the system antenna was not damaged; or (b) Operational checks were done without problems.

5.6.3 Understanding Impacts of Lightning Strikes on Aircraft Designs

Lightning not only impacts aircraft systems but also imposes sometimes significant impacts on airline operations. The ability to predict lightning is one way to begin the difficult task of reducing the impact of lightning on aircraft systems and airline operations. As discussed in Chapter 2, the mechanism of lightning strikes to aircraft were not well understood until the 1980s when tests convincingly demonstrated that the vast majority of lightning strikes to aircraft are initiated by the aircraft, as opposed to the aircraft's intercepting a discharge already in progress.

In August of 2004, a final report was delivered for a study of actual lightning strike effects on general aviation aircraft. The study was sponsored by U.S. Department of Transportation Federal Aviation Administration Office of Aviation Research Washington, DC 20591 and is titled, "General Aviation Lightning Strike Report and Protection Level Study" [5.14]. This report analyzed 95 lightning strike reports from general aviation business jet aircraft that occurred over a 5-year period. The analysis was conducted to determine which variables most affect the severity of indirect lightning effects damage of in-service aircraft and their systems and to assess the effect of the level of lightning and High-Intensity Radiated Fields (HIRF) protection design and implementation. The study found that fully protected aircraft had a significantly lower percentage of electrical failure and interference due to lightning strikes when compared to aircraft with no protection or only avionics protection. The number of electrical failures reported did not increase over the age of the aircraft.

The lightning strike data analysis for the Federal Aviation Administration and the National Institute of Aviation Research [5.14] was conducted to study and review lightning strike reports from incidents involving general aviation business jet aircraft. A lightning strike database was compiled during this study from forms filled out by pilots and maintenance personnel along with the corresponding maintenance history of that aircraft. The general purpose of the study was to develop a better understanding of the factors that are most influential in affecting the probability of electrical damage of in-service aircraft and their systems due to a lightning strike, to assess the cost-effectiveness of design changes, and to improve reporting and data collection procedures. There were 95 incident reports on various aircraft models in the database that were used in the study. After validating the data, three variables were studied with respect to lightning damage: aircraft age, aircraft flight hours, and the level of High-Intensity Radiated Field (HIRF) protection. In this study evaluation, a correlation to HIRF and lightning protection is not directly made but in many cases studied and except for specific HIRF protection circuit components within avionic equipment, many lightning protection components also provide HIRF protection. The level of HIRF protection for each aircraft model in the database was categorized as full protection, avionics protection, or no protection. Reporting of lightning strike incidents has drastically improved over the last 5 years, indicating the effectiveness of lightning strike incident-gathering procedures. Also, aircraft delivered over the last 10 years have been increasingly equipped with HIRF-protected systems. The data revealed that aircraft were most vulnerable to a lightning strike when flying in clouds and rain. This is consistent with the theory presented in Chapter 2 of this thesis regarding the nature of lightning strike development in the atmosphere. The study also found that the amount of HIRF protection in an aircraft had a significant impact on the extent of damage resulting from a lightning strike. Compared to unprotected aircraft, HIRF-protected aircraft had a significantly lower percentage of electrical failures or electrical interference events due to lightning strikes. The study indicated that the age of the aircraft had no observable impact on the percentage of electrical failures due to lightning strikes. This data may be held suspect since it is not consistent with specific findings of lightning protection degradation resulting in lower protection levels observed by industry OEM lightning protection engineers. The study however concluded that the percentage of electrical failures from lightning strikes increased for those aircraft with more flight hours.

Another data source refers to the impact of lightning strikes by evaluating lightning strike data [5.48] from five United States Commercial airlines. The purpose of the project was to obtain information on the conditions under which aircraft are most likely to receive lightning strikes in flight, and document the effects that these strikes have upon the aircraft. For this purpose, the airlines were provided with questionnaire-type reporting forms for use by pilots and maintenance personnel in documenting lightning strike events and effects on the aircraft. The motivation for the project stemmed from a need to obtain a better understanding of the conditions under which aircraft are struck, the places on the aircraft where strikes are most likely, and the effect of these strikes on the airframe as well as onboard electrical and avionics systems. Initial results from the project were published by General Electric in 1974. At that time, a total of 214 strike reports had been received. The data was useful to designers of lightning protection. For example, the strike reports helped clarify the locations of lightning strike zones on transport category aircraft, and alerted designers to potential lightning-induced voltage problems.

Strike reports continued to be received by General Electric at the time, but no further data summaries were published, and in 1977, the project was taken over by Lightning Technologies, Inc.; a lightning test and evaluation company in Pittsfield Massachusetts. By early 1984, nearly 800 lightning strike reports had been accumulated and Lightning Technologies, Inc. invited the Federal Aviation Administration Technical Center to participate in the project by computerizing each of the strike reports and processing the data. With the data in computer memory, it is possible to provide correlation among various reported conditions and effects.

The data collection program began with five participating airlines provided in a public report [5.48]: American, Braniff, Continental, Eastern and United. Economic factors at the time however, made it necessary for Braniff, Continental, and Eastern to cease participation. Thus, from 1980 to 1985, data was furnished only by United and American. These airlines, however, provide a large geographic data base at the time. The data from this early effort included lightning strike information from 10 different transport type aircraft from the aforementioned air carriers. The aircraft type included Boeing B707, B727, B737, B747, and the B757 and B767 aircraft. Also included were Douglas DC-B, DC-9, DC-10 and Lockheed L10ll aircraft.

The reported effects of the lightning strike were tabulated under the following headings; attachment points, interference/outage, effects on personnel, and electrical/electronic damage. For the attachment points, the exact location of 1ightning attachment points are generally observed during the post-lightning strike ground inspection. Due to the size of transport type aircraft 1 and the complexity of locating the exact attachment points, many times the attachment points are often not located and reported. This was evident .in analyzing the data, as a total of 672 did not indicate the attachment points. Of the total 253 attachment points recorded, 28 percent were to the nose of the aircraft, with approximately 50 percent reported to the fuselage at some point. The remainders of the attachments were divided equally between the wings and tail.

For the interference or system outage, from the total 783 reports, 87 reported outages. This is also referred to as the indirect effects of lightning. These outages required ground crew maintenance (either repair or replacement). The navigation systems had 30 instrument outages with only six communication systems impacted. Engine instruments had a total of 39 outages. More recent work on the study of lightning threats, locations and effects has addressed these types of indirect effects. This protection requires attention to the design for continued airworthiness.

In this work, a few cases of lightning strikes that have documented effects on the aircraft are included to provide a framework for why it is important to consider continued airworthiness of lightning protection within the design process. It is known that lightning protection can deteriorate over the life of an aircraft. An example might be a bond jumper use for earthing aircraft systems during a lightning strike event that corrodes over the years of use within corrosive environments exposed to runway chemicals and multiple weather changes.

5.7 Aircraft Lightning Strike Events and Case Studies for Direct Lightning

5.7.1 Results from Literature Search

The following events highlight the importance of maintaining the continued airworthiness of lightning strike protection. Each case report has been produced by government officials from the country in which the accident occurred. These examples demonstrate the results of direct and indirect effects that lightning strike events impose on aircraft and aircraft operations.

Event 1: Lightning Strike - SA 227, Metro III, February 8, 1988 on flight from Hanover to Düsseldorf, Germany

In 1988, a Fairchild Metro III commuter turboprop crashed on approach to Dusseldorf after a lightning strike had "apparently disconnected all batteries and generators from the aircraft's electrical system, also terminating the cockpit voice recorder record," according to an academic review [5.16]. The crash came after several attempts to land, and was blamed on "a combination of poor pilot judgment or skill and the lightning-caused electrical failure." Twenty-one people died.

The following are excerpts of a crash associated with lightning strike found in the German Luftfahrt-Bundesamt (LBA) Accident Investigation Bureau report [5.16].

Accident Details:
Date: February 08, 1988
Time: 07:58
Location: Near Mulheim, Germany
Operator: NFD - Nurnberger Flugdienst
Flight #: 108
Route: Hannover - Dusseldorf
AC Type: Swearingen SA.227AC Metro III
Registration: D-CABB
Aircraft production cn / ln: AC-500
Aboard: 21   (passengers:19 crew:2)
Fatalities: 21   (passengers:19 crew:2)
Ground: 0

Summary: The plane was struck by lightning and suffered a complete electrical failure after which the right wing broke off during an uncontrollable descent.

Reporting Agency: The Luftfahrt-Bundesamt (LBA)
The LBA (German for Federal Agency of Aviation) was established as the supreme Federal Authority to fulfill tasks in the field of civil aviation. It is subordinated to the Federal Minister of Transport, Building and Urban Affairs. The LBA consists of the Headquarters in Braunschweig and the Regional Offices in Düsseldorf, Frankfurt/Main, Hamburg, Munich, Stuttgart and Berlin. The tasks of the Luftfahrt-Bundesamt are laid down in the LBA Act (Gesetz über das Luftfahrt-Bundesamt). The most important goal of the LBA is to avert hazards to the safety of aviation as well as to public safety and order.

[5.16] The most serious aircraft accident, which occurred in the Federal Republic of Germany in the last 20 years, has to be attributed to the effects of lightning strike. On February 8, 1988 a SA 227-AC, Metro III, was on a scheduled flight from Hanover to Dusseldorf, with 19 passengers and 2 crewmembers on board, when in initial approach approximately 7 miles (NM) from the threshold, the electrical power supply failed in a thunderstorm after the airplane that been struck into uncontrolled descent and after two minutes' flying through the thunderstorm region disintegrated in the air. In the following impact all occupants were killed and the airplane was destroyed. In the concluding investigation report the investigation commission established that an electrical failure caused by lightning strike under instrument landing conditions, which also resulted in the failure of the cockpit and instrument lightning and made an actuation of the landing flaps and horizontal stabilizer trim impossible, has mainly contributed to the accident. An especially dramatic factor was that the damage caused to the diodes in the electrical system probably made the crew unable to restore the power supply.

Explanation of the activities leading to the Metro III accident:
During the climb of an SA 227, Metro III, from FL 140 under instrument flight conditions, the airplane was struck by lightning. According to the report of the crew, the total electrical power supply system failed suddenly. The pilot-in-command immediately took over the controls as provided for in the air carrier's Flight Operating Manual (FOM) in such cases. With the switches for the operation of the electrical power supply system located directly in front of the pilot on the left seat, he had immediately after that, let the co-pilot take over the controls again, who managed to continue the flight by means of the built-in third artificial horizon. The pilot on the left seat was then able to concern himself with the restoration of the electrical system for which a certain order in the operation of the battery and generator switches was required to be strictly observed (see also "Total Electrical Failure" in the Airplane Flight Manual, Metro III Emergency Procedures).

In this case, according to the report, an accident could be prevented. The pilot was familiar with the procedure "Total Electrical Failure", which after a recent accident had been incorporated in the Airplane Flight Manual based on a safety recommendation. The "Crew Coordination" in the cockpit worked well. The diodes in the electrical power supply system, which probably prevented the restoration of the electrical supply, have been removed in accordance with a safety recommendation issued by the Accident Investigation at LBA (FUS) resulting in an AD.

According to the report, due to the constructional characteristics of the electrical power supply system it cannot be excluded for the types SA 226 AT and SA 226 TC and its models, including the SA 227 AC, Metro III, that the danger of a total electrical failure as a result of lightning strike continues to exist. For this reason the FUS recommends all pilots flying these types:

(1) to observe the procedure "Total Electrical Failure" in the Airplane Flight Manual and practice the required actions in the simulator or in a ground training on the airplane.
(2) to be prepared for a failure of the electrical power supply system in weather situations with the danger of lightning. That means, among other things, that o torch should be at hand, ready for use.
(3) to take off the headphone after a lightning strike with total electrical failure. A communication by the Intercom System is no longer possible then.
(4) to observe the position of installation of the third artificial horizon. The location in the cockpit panel can differ from airplane to airplane.

Significant aircraft findings regarding effects of lightning strike:
Though the investigation did not directly identify a failure of lightning protection as the cause for the Metro III incident, it has correlated the lightning event with the electrical system failure and subsequent crash. Emergency procedures have been revised in the Airplane Flight Manual section under, “Total Electrical Failure” to include direction to investigate lightning strike damage after the event. The update

includes the following text, “If total electrical failure occurred as a result of lightning strike or discharge, the aircraft should be thoroughly inspected for evidence of lightning damage. See the SA227 Maintenance Manual, Chapter 05 and the TPE 331 Maintenance Manual, Chapter 72. FAA approved May 22, 1989.

In normal operations, aircraft inspections are required after lightning strike events. This work recognizes the need for a design methodology for the continued airworthiness of lightning protection. The new design methodology proposed, will reduce the number of events resulting in catastrophic conditions.

Event 2: Lightning Strike - SA 227, Dornier DO 228-202, December 4, 2003 on flight KAT603 from Rost Airport (ENRS) to Bodo Airport (ENBO), Norway operated by Kato Airlines AS

On Thursday, 4 December 2003 at time 0915, the Head of Air Traffic Control at Bodø control tower telephoned the duty Inspector of accidents at the Accident Investigation Board Norway (AIBN) to notify about an accident involving a Dornier DO 228 aircraft. The notification stated that a Dornier 228 belonging to Kato Airline had crashed just east of the threshold of runway 25 at Bodø Airport, and that the status with regard to the four people onboard was unclear. Shortly after, the AIBN received similar notification from the Police's operation centre and from Kato Airline.

Because of poor weather conditions in Bodø and the fact that the east part of the runway was closed, it was for a time uncertain whether the AIBNs scheduled flight would be able to land at Bodø airport. The AIBN managed to turn out with three accident inspectors, who arrived at the accident site at 14:50 on the same day.

The following are excerpts of the crash associated with lightning strike found in an official accident investigation report [5.17] within the (AIBN).

Accident Details:
Date: 4 December, 2003
Time: 0909 local time (UTC + 1)
Location: Bodo Airport, Norway
Operator: Kato Airline AS
Flight Number: Kato Airline flight KAT603
Route: From Røst airport (ENRS) to Bodø airport (ENBO)
Aircraft Type: Dornier DO 228-202
Registration: LN-HTA
Accident site: Bodø airport (ENBO), threshold of runway 25
(67°16’2’’N 014°24’0’’E)
Aboard: 4 (passengers: 2 crew: 2)
Aircraft Production: S/N 8127 Manufactured in 1987
Fatalities: 0
Ground: 0
Injuries: 2 Serious and 2 minor

Summary: The plane was struck by lightning and suffered a broken control rod in the horizontal stabilizer due to large amounts of current present during the strike making the aircraft difficult to control in pitch direction.

Reporting Agency: Accident Investigation Board Norway (AIBN)
The Norwegian Accident Investigation Board is a government-funded investigation board, whose task is to investigate accidents and incidents within the aviation, marine, road and railway sectors (including underground railways and tramways).

The activities of the Accident Investigation Board are based upon the Norwegian Air Navigation Act of 1923. At that time, the board was under the administration of the Ministry of Defense and accidents were investigated by ad hoc boards.

In 1944, the Convention on International Aviation was ratified and a special organization under the aegis of the UN was created - the ICAO, the International Civil Aviation Organization. A total of 187 countries, including Norway, are members of this organization. The international agreements are collected in 18 annexes. Annex 13 concerns investigation of aviation accidents and incidents, and the board bases its work on this annex which describes the methods of aviation accident investigation.

A new regulation was introduced in 1988 for the investigation of aviation accidents, and on 1 January 1989 a permanent board, under the administration of the Ministry of Transport, was established. This board became autonomous on 1 July 1999.

The regulation concerning official investigations states that the investigation has as its goal clarification of the sequence of events and causes, as well as discussing other significant conditions that could prevent accidents and incidents in order to improve aviation safety. The purpose of the investigation is not to apportion liability.

The Investigation Board itself decides the scope of the investigations that are to be conducted, including the assessment of the expected safety benefit from an investigation in relation to the resources expended.

Explanation of the activities leading to the DO 228-202 accident:
Kato Airline flight KAT603, an aircraft of the type Dornier 228-202 with registration LN-HTA, was to fly a regular scheduled flight from Røst airport (ENRS) to Bodø airport (ENBO). There were two passengers and two pilots on board. There was a strong westerly wind, and when the plane approached Bodø extensive lightning activity developed quickly. The aircraft was struck by lightning. The lightning struck the aircraft’s nose area and passed to the tail. Earthing wires between the fuselage and tail surface and a wire between the tail surface and the elevator were burned off. A powerful electric energy passed through the elevator rod in the tail section. A rod end came loose, resulting in a breach in the control rod. Thus the only connection between the control column in the cockpit and the elevator was lost. After a period, the pilots regained limited control of the aircraft’s nose position by using the aircraft electric pitch trim which adjusts the tail surface angle of attack.

When the lightning struck the aircraft, the pilots were blinded for approximately 30 seconds. They lost control of the aircraft for a period and the aircraft came very close to stalling. The pilots declared an emergency. The aircraft's remaining systems were intact and the pilots succeeded in bringing the plane in for landing. During the first landing attempt the airspeed was somewhat high. The aircraft hit the ground in an approximate three-point position and bounced into the air. The pilots concluded that the landing was uncontrollable because the elevator was not working. The landing was aborted and the aircraft circled for a new attempt. Wind conditions were difficult and the next attempt was also unstable in terms of height and speed. At short final the aircraft nosed down and the pilots barely managed to flare a little before the aircraft hit the ground. The point of impact was a few meters before the runway and the aircraft slid onto the runway.

Emergency services quickly arrived at the scene. The two pilots were seriously injured while both passengers suffered only minor physical injuries. No fuel leakage or fire occurred. The aircraft was written off. There is reason to believe that the total amount of energy in the lightning exceeded the values of the construction specifications. The investigation has uncovered that up to 30% of the wiring in essential earthing wires in the tail may have been defective before lightning struck. Other relevant safety issues that are discussed in the report are the need for increased focus on maintenance and the optimum use of airborne weather radars. The investigation has further uncovered a need for better presentation of information from ground-based weather radars by the air traffic control service.

Significant DO 228-202 aircraft findings regarding effects of lightning strike and lightning strike protection airworthiness**:**
The specific aircraft involved in this crash was registered according to regulations and had a valid airworthiness certificate. As part of the investigation result, nothing was discovered to indicate that the aircraft was not maintained in accordance with approved inspection procedures. The lightning strike caused severe damage shown in Figure 5-11 to the horizontal stabilizer. However, operations of the rod between the cockpit and elevator after the lightning strike was found to be impaired though the rod is not required to function as a designed current path to carry lightning currents during a lightning strike.

Figure 5-11 Lightning strike damage to the DO 228 right elevator

The transfer rod to the elevator was broken when the lightning travelled through the aircraft. This made it no longer possible to control the elevator. The control rod depicted in Figure 5-12 was an alternate path to carry the large current form a lightning strike. It is common in lightning strike events to have large current from the strike transfer between the nose of the aircraft and exit out the tail of the aircraft. As many lightning strike events contain a large variance of current, any single lightning strike may not result in any effect on the aircraft. This is why the design requirements use the worst likely case in each location of the aircraft to determine the potential voltages and lightning current that may be present during a strike. At the time of the design, tools are used to demonstrate the potential lightning threat in each aircraft location and in cases where lightning current and voltage are undesirably high, additional protection of the aircraft and equipment may be recommended to add to the final design. These lightning protection techniques need to remain available throughout the life of the aircraft to ensure that any lightning strike event would not result in a potentially catastrophic condition. In the case of this Dornier DO 228, bond straps (earthing wires) were included in the horizontal stabilizer to reduce unwanted high levels of current and voltage.

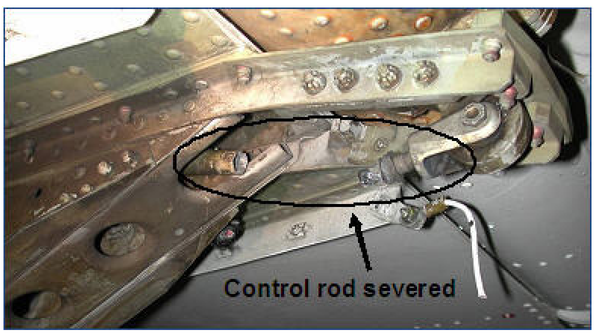


Figure 5-12 Broken Elevator Control Rod on DO228

Fortunately in this case, it was possible to use electric trim to control the aircraft's horizontal stabilizer and therefore, to a certain extent, the aircraft's pitch after the lightning strike current broke the control rod. According to the aircraft crew, the aircraft's weather radar did not indicate the precipitation cells. This is an indication that the weather radar was not functioning correctly.

Noted as an investigation finding, up to 30% of the wires on individual earthing between the fuselage, horizontal stabilizer and elevator may have been broken before the lightning struck the aircraft. It is also estimated by examination of the direct effects damage that the aircraft was hit by lightning containing a very large amount of energy. Conclusions in the investigation determined that the aircraft's earthing wires were not able to conduct the electric energy from the lightning and the transfer rod from the cockpit to the elevator was broken. Examination of the earthing wires in the horizontal stabilizer shown in Figure 5-13 point to several breaks in the bonding connections between the elevator and the fuselage.

Figure 5-13 Broken, burn and damages earthing wire from horizontal stabilizer structure to fuselage

In the design of the DO 228 aircraft lightning protection, bond jumpers are installed in six locations on the empennage to assist in diminishing the effects of a lightning strike event. Figure 5-14 shows the approximate location of the bond jumpers in that design where two bond jumpers are installed between the stabilizer and the empennage and 4 bond wires are installed between the stabilizer and the elevators.

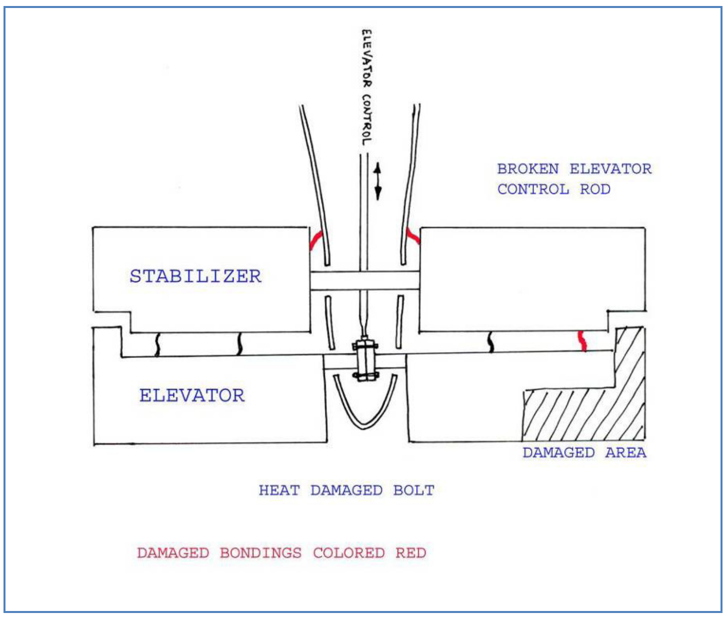


Figure 5-14 Lightning protection bond wires in the horizontal stabilizer

The strike path in this event was most likely initiated at the nose of the aircraft and transmitted along the fuselage to the stabilizer through these two bond jumpers and then from the stabilizer to the elevators and then continued to depart the aircraft. After further investigation of the hull, it was noted that high on the nose left side of aircraft there were two small burn marks. Figure 5-15 shows burn marks on the aircraft nose near the nose radome attach point to the aircraft, burn marks on the pitot tube fastener and another burn mark on the baggage handling door hinge just behind the nose radome. Burn marks are common after a lightning strike. Upon each lightning strike, a procedure to inspect the burn marks, potential lightning entry point and exit point is necessary to minimize the impact of potential further degradation of lightning protection and exposure to a potentially catastrophic condition. In the case of this DO228 accident investigation [5.17], no damage was found inside the aircraft. It was found upon deeper evaluation of the control rods in the cockpit that several bolts and bearings in the elevator mechanism had suffered heat damage when the current passed through.

Figure 5-15 Burn marks on the nose, pitot tube & baggage handling door hinges

As a result of the reduced control of the aircraft's pitch and difficult wind conditions, the sink rate was not sufficiently stabilized on short final. The crew was unable to prevent the aircraft from hitting the ground.

It can be determined from the investigation that broken or missing earthing wires resulted in this potentially catastrophic event. From the inspection of the hull after the lightning strike event, it was determined that bond jumpers were missing and the remaining bond jumpers were severely damaged. During the dismantling of the elevator, damage to one of the four bolts holding the two halves of the right elevator together was also discovered. The bolt which also holds the corner where the elevator rod was fixed had gradually melted.

Impact of carbon fiber composite structural components used as an alternative to aluminum or other metallic structural components has a significant impact on lightning protection designs, the inclusion of lightning protection, and the long term availability of good bond paths. Upon inspection and as can be seen in Figure 5-11, the right elevator structure in this accident was missing approximately half of its fabric covering. About half of the carbon fiber cover on the end of the horizontal tip was also missing, including the elevator's outer static discharger. The outer right corner of the elevator's aluminum structure was also burnt off.

With the help of an ohmmeter, a break in the electric connection between the elevator and the fuselage was discovered. Closer examination revealed several breaks in the bonding connections between the elevator and the fuselage as noted by the bond jumper damage. It is noted that with the bond jumpers missing, almost the entire bonding on the outer bonding connection to the right elevator is not in place. During a lightning strike event with the reduced available current conduction path and in addition, a higher resistance material for outer structure (composite), a greater current will flow in the remaining conductive path through the available bond jumpers and the elevator control rod. In addition, both fasteners holding the bracket to the bonding jumper had melted leaving the bracket loose in the space between the elevator and the horizontal tail surface. Figure 5-16 shows the damaged bond jumpers and bracket contributing to the reduced lightning protection.

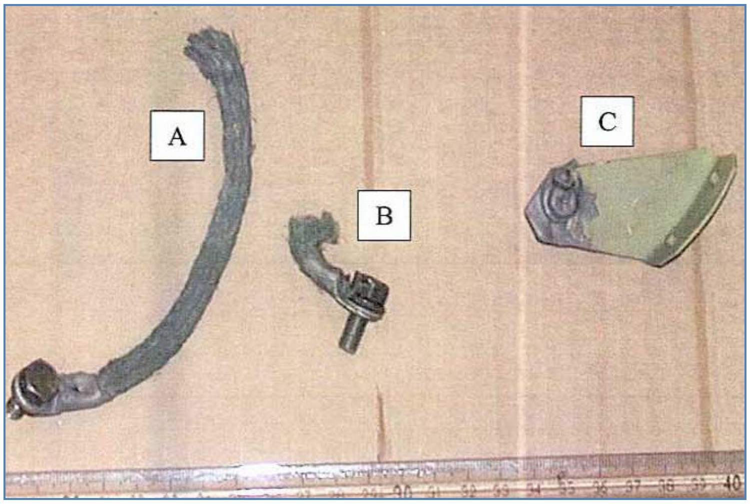


Figure 5-16 Damaged bond jumpers (earthing wires) loose and damaged bracket

The lightning protection design for the DO228 and many other transport category aircraft is very simple but also critical in providing continued safe flight and landing of the aircraft. In this DO228 design, upon further inspection, it was noticed that the braided bond jumpers were frayed, broken and corroded as shown in Figure 5-17. The use of materials that contain corrosion resistive coatings, compatible materials, and appropriate sealants in aircraft locations where environments are considered in detail, have to be weighed against the requirements for adequate conductive properties and long lasting solutions. When designing the conductive path for lightning protection, redundancy is important but also the understanding of common-mode degradation that may reduce the lightning protection simultaneously is also critical to mitigate these reduced protection conditions.

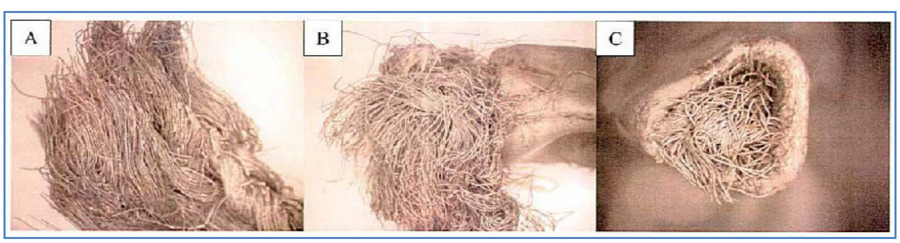


Figure 5-17 Bond jumpers damaged due to environmental effect degradation

The known degradation of the bond jumpers prior to the lightning strike reinforces the practice of lightning strike inspections for all lightning protection after each strike. Also involved in the continued airworthiness of the lightning protection is the scheduled maintenance program guidance. Bond jumpers are critical elements in the protection scheme and should be evaluated at the time of design for the need to maintain the protection with periodic inspections. In experience with other bond jumpers on other aircraft, degradation of the braided bond jumper design is experienced and should be evaluated when determining the environment of each bond jumper installation as proposed by this work.

In the investigation of the DO228 aircraft crash, it was discovered that there was no electric connection between the horizontal tail surface and the fuselage. The reason for this was found to be that the tail surface was fixed by means of bearings with Teflon coating. Consequently, the horizontal tail surfaces became electrically isolated from the fuselage when the bonding connections broke. The use of a bind path analysis is necessary to ensure that alternate bond paths are well understood in cases where the primary design bond path is compromised. Lightning currents are not forced to follow the designed conduction paths and may find alternative conductive routes through the aircraft structure. In these cases, and especially when using composites as the primary structural element in the design, the larger voltages caused by the failure of the primary conduction path can cause unwanted currents across otherwise non-current carrying paths such as bearings and flight control surface hinges. In case of failures to lightning protection, a good design methodology such as proposed in this work will evaluate the long-term availability of protection within a given installation environment.

Subsequent to the event and investigation, the Accident Investigation Board Norway issued three safety recommendations.

1. Safety Recommendation SL no. 2007/22T:
A functional airborne weather radar system and optimal use of such a system are important in localizing precipitation cells and thereby avoiding flying into areas with hazardous flying conditions. The AIBN recommends that the Norwegian Civil Aviation Authority and Kato Airline assess the best way of focusing on maintenance of airborne weather radars and training in their optimal use.

2. Safety Recommendation SL no. 2007/23T:
Presentation of weather on the air traffic control service's radar displays is important in avoiding aircraft being radar vectored into areas with hazardous flying conditions. The AIBN recommends that Avinor assess integrated presentation of information from weather radars on the air traffic control service's radar displays.

3. Safety Recommendation SL no. 2007/24T:
Up to 30% of the wires on individual earthing wires between the fuselage, horizontal stabilizer and elevator may have been broken before the lightning struck. For example, the maintenance requirements issued by Dornier Luftfahrt GmbH are not specific with regard to the condition of the aircraft's earthing wires. The AIBN therefore recommends that the Norwegian Civil Aviation Authority consider issuing additional maintenance requirements for aircraft type DO 228 with regard to the capacity to withstand lightning.

5.7.2 Conclusions from Literature Search

The Importance of Lightning Strike Protection Continued Airworthiness Design

The previous two accident cases demonstrate the potential impact of a lightning strike protection design that is not adequate to for the continued airworthiness of the aircraft during its life expectancy. This event validates the reasoning for a new design method associated with the continued airworthiness of lightning strike protection. From the two case investigations above, it is clear that designs require evaluation as to the continued availability of the protection during the entire operating life of the aircraft at the time of the design decision. With the inclusion of proper maintenance procedures combined with appropriate designs that recognize operating environments as a threat to the continued airworthiness of these designs, one can derive the methodology proposed in this work to modify current design practices that combine both maintenance procedures and design features into one robust lightning protection result. Given successful implementation of the design methodology proposed in this work, more robust design results are expected that will improve performance of systems and structures before, during, and after lightning strikes to the aircraft. Though the proposed methodology will not reduce the amount of damage found after a lightning strike, increased continued availability of lightning protection that will maintain appropriate safety levels and perform as designed throughout the life of the aircraft is an expected outcome for aircraft designers that use the design methodology proposed in this body of work.

5.7.3 Case Studies Conducted within Body of Work

The following case studies will use existing aircraft data to exercise the proposed methodology. Multiple case studies are conducted to test the methodology using several very different lightning protection types. For these case studies, lightning protection for the airplane is in four major areas:

1. Aircraft Structure
2. Fuel Systems and Ignition Prevention
3. Antenna protection due to direct lightning attachment
4. System wiring, bonding and grounding protection due to magnetic and electric field coupling

In order to start the case studies, the following text will provide technical details necessary with regard to the specific airplane lightning protection design.

5.7.3.1 Lightning Protection Design Zones for the Aircraft in the Case Studies

Frequently, a lightning strike is referred to as a static discharge. This incorrect reference sometimes causes confusion about the purpose of static dischargers (small rod devices) installed on the tips and trailing edges of airfoils shown in Figure 5-10. These devices do not prevent the lightning strikes on the airplane. The primary function of the static dischargers is to bleed off the static charge on the airplane. This is to prevent static radio interference in the airplane avionics receivers such as the VHF communication radios, automatic direction finding system (ADF), and Very High Frequency Omni-directional Range (VOR) systems. The static dischargers are frequently hit and damaged by lightning. Some of them are installed at a specified point as protection to a light or other system component. This is an added function beyond their normal function of static bleed off. Static discharges are not part of the lightning protection case studies.

Lightning strike zones for the aircraft in the case studies have been determined through a process of assessment for probabilities of attachment and locations where lightning strike occurs. Using the relationship between aircraft lightning environment, lightning zone, and testing, the aircraft designers determined the lightning zones for the aircraft in the case studies as shown in Figures 5-18 and 5-19 to be used in design of the associated lightning protection. The lightning zones within the aircraft under study and the associated threats of lightning current were determined using the following guidance for lightning zones. There are three major zone divisions as described in Figure 5-18 and Figure 5-19 representing:

1. Likely regions for initial lightning attachment and first return strokes.
2. Regions which are unlikely to experience first return strokes but which are likely to experience subsequent return strokes. This will happen where the aircraft is in motion relative to a lightning channel causing sweeping of the channel backwards from a forward initial attachment point.

Regions which are unlikely to experience an arc attachment, but which conduct lightning current between attachment points are included in the region explanation. Regions 1 and 2 are subdivided into specific lightning attachment zones as follows:

- Zones 1A and 2A, where long hang-on of a lightning channel is unlikely because the motion of the aircraft with respect to the channel causes the attachment point to move across the surface of the aircraft in the opposite direction from the direction of motion.
- Zones 1B and 2B, where the lightning channel attachment point is unlikely to move during the remainder of the flash because the location is a trailing edge or a large promontory from which the relative motion of the aircraft and channel cannot sweep the attachment point further.

Specific zone definitions for the Aircraft in these Case Studies

- Zone 1A - First return stroke zone: All the areas of the aircraft surfaces where a first return stroke is likely during lightning channel attachment with a low expectation of flash hang on.
- Zone 1B - First return stroke zone with long hang-on: All the areas of the aircraft surfaces where a first return stroke is likely during lightning channel attachment with a high expectation of flash hang-on.
- Zone 2A - Swept stroke zone: Aircraft surfaces where subsequent return stroke is likely to be swept with a low expectation of flash hang-on.
- Zone 2B - Swept stroke zone with long hang-on: All the areas of the aircraft surfaces into which a lightning channel carrying a subsequent return stroke is likely to be swept with a high expectation of flash hang-on.
- Zone 3 - Those surfaces not in Zones 1A, 1B, 1C, 2A, or 2B, where any attachment of the lightning channel is unlikely, and portions of the aircraft beneath or between the other zones and/or conduct substantial amount of electrical current between direct or swept stroke attachment points.

The location of these zones on the aircraft is agreed between the applicant and the certification authority as proposed in Figure 5-18 and 5-19. As described in Chapter 2 of this thesis, the specific electrical threats associated with lightning in each of the aircraft lightning zones were determined in accordance with FAA Advisory Circular AC 20-53A [5.1] and guidance from both SAE ARP 5414 [5.47] and SAE ARP 5412 [5.28]. Table 5-8 provides typical current values for each lightning strike type.

Zone	Lightning Attachment Mechanism	Location	Typical Current
1	Initial Strike, first return stroke	Wing tips, wing leading edge, wing trailing edge, rudder tips, engine leading edge, radome	200kA
2	Swept stroke	Fuselage, wing surface behind engines	100kA
3	Current Conduction	Wing surface, rudder surface, horizontal stabilizer surface	30kA

Table 5-8 General description of defined lightning threats

Proprietary Graphic Retained

Figure 5-18 Aircraft Lightning Zones Locations (Top View)

Note: Details of aircraft lightning zone schematics are contained in the Proprietary Appendix to protect the proprietary nature of the information.

Proprietary Graphic Retained

Figure 5-19 Aircraft Lightning Zones Locations (Side View)

Note: Details of aircraft lightning zone schematics are contained in the Proprietary Appendix to protect the proprietary nature of the information.

In order to determine the lightning zones, a relationship between the lightning phenomenon and the physical configuration of the aircraft in these case studies was determined. Lightning zoning is a functional step in demonstrating that the aircraft is adequately protected from both direct and indirect effects of lightning. The purpose of lightning zoning is to determine the surfaces of the aircraft which are likely to experience lightning channel attachment and the structures which may experience lightning current conduction between pairs of entry/exit points.

Zoning of the aircraft in these case studies was determined along with the aircraft hazard assessment to determine the appropriate protection for a given aircraft part or location. To determine the appropriate protection for parts and structure on the aircraft, in a particular lightning zone, the criticality of the systems or structure in the zone was considered. The method of development that led to the aircraft lightning strike zone map is described in Figure 5-20 which provides graphic representations between design and test practices that led to the direct effects protection configuration examined within this research.

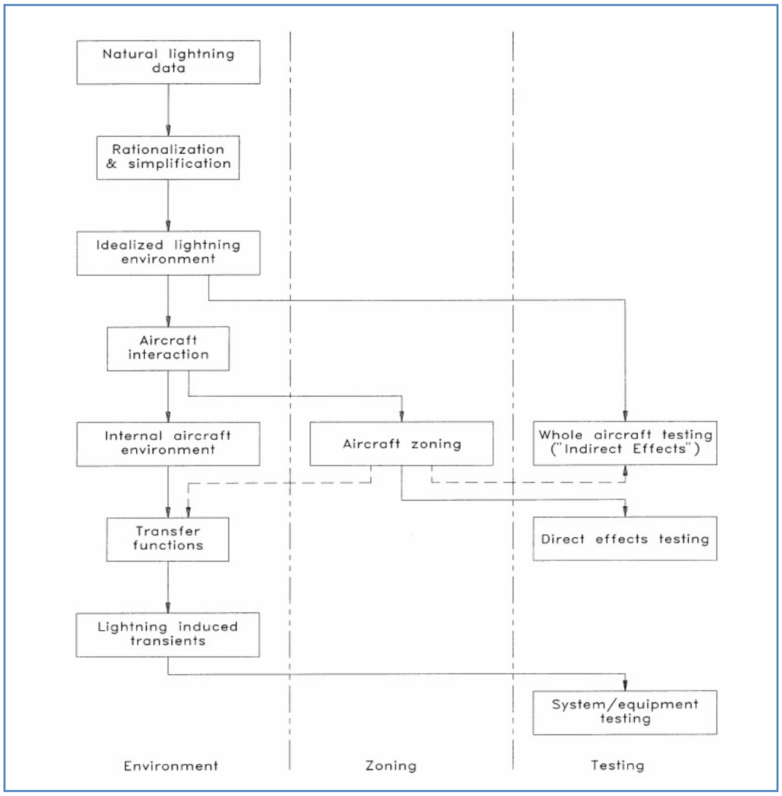


Figure 5-20 Determination of the aircraft lightning strike zones

External radome and antenna installations also receive a larger number of direct attachments for which the aircraft requires protection. When assessing lightning protection continued airworthiness, it is important to create a list of all lightning direct and indirect effects protection.

Table 5-9 provides a comprehensive list of aircraft lightning protection for the aircraft under evaluation in these case studies. As part of demonstrating the methodology contained in this work, certain lightning protection components will be selected from the installed list and evaluated for continued airworthiness using the design evaluation sheets proposed in the methodology validation section of this thesis. During an aircraft design project, the collection of protection planned for each part of the aircraft is an important initial step to the deployment of this methodology. Though the systems contained in Table 5-9 are already designed, the case studies will evaluate each design as if it were part of the design process as shown in Figure 5-1 as "Lightning protection continued airworthiness and maintenance requirements". Appendix E contains terms and definitions of terms used in the design and determination of aircraft Zones and the establishment of direct effects lightning threats for those lightning zones.

Direct or Indirect Protection	Protection Type	Aircraft Location	System/Structure
Indirect	Wire Loom Shielding	Wing	Flight Controls
Indirect	Wire Loom Shielding	Engine	Engine Controls
Indirect	Wire Loom Shielding	Strut	Fuel & Engine Controls
Indirect	Wire Loom Shielding	Fuel Tanks	Fuel System measuring and indication
Indirect	Wire Loom Shielding	Vertical Stabilizer	Flight Control
Indirect	Wire Loom Shielding	Wing to body Fairing	ECS
Indirect	Wire Loom Shielding	Horizontal Stabilizer	Flight Control
Indirect	Wire Loom Shielding	Empennage	Auxiliary Power Unit
Indirect	Wire Loom Shielding	Fuselage Internal	Multiple Avionics & Electrical
Indirect	Wire Loom Shielding	Flight Deck	Avionics control & indication
Indirect	Wire Loom Shielding	Electrical & Avionic Equipment Bay	Avionics & electrical control
Direct	Structural Bond – Antenna installations	Antenna penetrations through structure and radome protection	Communication and navigation installations
Direct	Structural Bond – Bond jumpers	Flight control surfaces, access panels	Flight control mechanical equipment Strut fairing composite structure
Direct	Structural Bond – Picture frames (added conductive materials to aircraft surfaces)	Wing Tips, rudder tip and rudder upper trailing edge	Wing composite structure
Direct	Structural Bond – conductive mesh	Wing leading and trailing edge	Wing composite structure
Direct	Structural Bond – Expanded Aluminum Foil	Nacelle and strut skin	Nacelle and strut composite structure
Direct	Structural Bond – aluminum skin thickness	Fuselage and wing metallic structure	Fuselage, wing and fairings
Direct	Structural Bond – Flame Spray	Keel Beam	Antenna ground paths
Direct	Structural Bond – Diverter strips	Fuselage installed antennas, nose radome	VOR, ILD, glideslope

Table 5-9 Aircraft Lightning Protection and locations for the aircraft in these case studies

Lightning zoning of the aircraft examined in these case studies is a fundamental design development step in determining appropriate lightning protection for the aircraft. Guidance on lightning zoning is currently contained in US Federal Aviation Regulations pertaining to fuel and electrical or electronic systems protection, however, because of the general application of lightning zoning to protection of all parts of an aircraft, the zoning development information has been updated, and presented in the SAE Aerospace Recommended Practices ARP5414 [5.47]. The ARP5414 includes clarification of the original zone definitions, introduction of a transition zone between Zones 1A and 2A, consideration of the effects of swept lightning leaders, and clarification of the influence of small protrusions on zoning. All of these design criteria were used in the development of the aircraft lightning zones and associated protection designs against the direct effects of lightning.

Aircraft lightning zones are created to assist with lightning protection design criteria in different locations of the aircraft. These techniques have been developed by the SAE ARP 5414 [5.47] to assist designers with creating the lightning zone map. The reason for this guide is to provide aircraft designers an actionable technique for the development of lightning protection designs within the different lightning strike zones. Key to deployment of the guidelines in SAE ARP 5414 is the definition of lightning strike probabilities correlated to different aircraft lightning strike zones. Over many years of experience and testing the probabilities of lightning strike attachments in different locations has been observed. This SAE guide provides a way forward to differentiate different locations of the aircraft that are likely to experience different threats from lightning energy. In a study conducted by the national Institute of Aviation Research conducted at Wichita State University on 95 business jet aircraft over a period of 5 years, information was gathered on damage caused by lightning strikes [5.14]. In this report a survey was taken from the Electromagnetic Effects Harmonization Group (EEHWG) Document WG-46 that resulted in a general description of the zone strike percentages from different contributors within the industry. The early development of this data generated Table 5-10 which was used as one source of information in the determination of lightning zone methodology. As can be determined from Table 5-10 (taken from General Aviation Lightning Strike NASA report), the leading aerospace companies in the industry have provided data that shows Zone 1 to experience strikes between 55 and 87 percent of the time, zone 2 12 to 41 percent of the time and zone 3 from zero to 23 percent of the lightning strikes. In general, the data, demonstrates the industry general agreements that Zone 1 including the radome and wing tips is more threatened by lightning strike attachment while zone 2 including areas on the bottom of the fuselage and wing tips and zone 3 which includes large areas under the wings are much less likely to be threatened by lightning strike attachments.

Company	Zone 1 (%)	Zone 2 (%)	Zone 3 (%)
Boeing Data	87	12	1
Airbus Data	66	34	0
Dessault Data	55	22	23
Fokker Data (jets)	53	41	6
McDonnell Douglas Data	69	27	4

Company	Zone 1 (%)	Zone 2 (%)	Zone 3 (%)
Lightning Strike Database	77	20	3

Table 5-10 Lightning strike distribution of aircraft manufacturers

For the case studies in this body of work, the author has examined the lightning zone maps for the aircraft under study. Representative maps have been included within the case studies. Data from the lightning strike studies generally confirms that the lightning zoning map in these case studies is consistent with other industry data. For the purpose of demonstrating the design methodology, a general understanding of the lightning zoning and lightning attachments threats in each part of the aircraft is helpful. The assessment sheets used within the case studies include a reference to the lightning strike zone within which the protection is installed. The methodology however, does not perform special assessments for different aircraft lightning zones since all the lightning protection is considered equally important, regardless of the lightning threat in the specific area where the lightning protection is deployed.

Aircraft Structural Protection for the Case Studies

The aircraft in these case studies has inherent lightning attenuation characteristics provided by the primary and secondary structure of the airframe, the details of which are discussed below. Structures and systems installations similar to those on certified airplanes produced by the manufacturer of the aircraft in these case studies have been verified for direct effects lightning certification by similarity. Non-metallic structures covering flight critical control components and cabling have been verified by analysis and/or engineering tests to prevent puncture by lightning. Engineering tests will use waveforms of [5.1] Advisory Circular (AC) 20-53A applicable to the location of the non-metallic structure.

The basic metallic and carbon composite structure acts as a shield which protects the internal areas from lightning strikes. The primary structure protects the electrical systems and wiring from lightning and electromagnetic interference. Conductive coatings on the flight deck windows for window heat provide lightning attenuation with no additional modifications required to protect the aircraft and crew.

Non-Metallic Structural Components Description

Non-metallic surfaces will be designed to meet the lightning environment for the zone in which they are located. The non-metallic surfaces will prevent a direct lightning attachment to any underlying electrical/electronic, or fuel wiring or aircraft components performing functions that are safety-related. During design of the aircraft, the structural protection requirements and designs develop through a process of test, determinations of past installation techniques that may be also effective for the new design, and development of the lightning zones. Structural lightning protection for the aircraft in these case studies consists of the following:

1. Structure surrounding antenna penetrations and bonding antennas use equipment shielding on connectors and direct grounding to structure. Direct grounding to structure can be accomplished by fay surface bonds between structural elements and the component shell or via bond jumpers.
2. Radome lightning diverters

    a. Include surface mounted diverter strips
    b. Bonding clips attached to the edge of the radome bonds each diverter strip to structure
3. Structural component bond straps (or earthing cables)
    a. Access panels
    b. Spoilers
    c. Flaps
    d. Ailerons
4. Wing tip structure
    a. Metallic strips mounted to the wing tips act as two dimensional faraday cage on composite structure to minimize damage after lightning strike
5. Wing Leading Edge and Trailing Edge
    a. Protection mesh or metallic coating on outer layer of composite skin
6. Nacelle and Strut Fairing
    a. Expanded Aluminum Mesh (EAF) on strut skins
    b. Bonding straps
    c. Other metallic materials such as Aluminum and Corrosion Resistant Steel used in the cowl and strut areas are both tested and proven to be inherently resistant to lightning puncture.
7. Fuselage protection
    a. Aluminum fuselage skins are designed with adequate thickness to prevent puncture and unwanted attachment to underlying systems
8. Wing to body fairing
    a. Expanded Aluminum Foil (EAF) mesh embedded in the wing to body structure
9. Keel beam panel
    a. Flame Spray used to provide additional protection from puncture and attachment to underlying systems and also to provide a ground path for externally attached antenna
10. Wing to body fairing environmental control system door
    a. Aluminum
11. Empennage control surface and antenna protection
    a. Diverter strip for VOR navigation antenna cover on centerline of cap
    b. Aluminum picture frame to CFRP on Rudder Tip and upper trailing edge bonded to structure using bonding jumpers
12. Tailcone
    a. Inherent protection provided by surrounding metallic aluminum structure
13. Rudder
    a. Metallic strips on upper and lower surfaces of the composite structure to minimize damage after lightning strike
    b. Expanded aluminum mesh on forward section of rudder tip to minimize damage due to lightning strike
    c. Bonding straps for some external skins and control surfaces that attach to surrounding structure
14. Horizontal Stabilizer
    a. Metallic strips on upper and lower surfaces of the composite structure to minimize damage after lightning strike

b. Expanded aluminum mesh on horizontal stabilizer tip to minimize damage due to lightning strike
c. Bonding straps for some external skins and control surfaces that attach to surrounding structure

Additional protection, separate from the structural protection system, has been added to specific communication and navigation antennas to prevent significant damage and adverse effects to the system components. The following methods were used to protect the communication and navigation systems:

1. Inherent "shielding" of the antennas from direct attachment by virtue of their location with respect to surrounding structure or conformal configuration.
2. System architecture to stand off unwanted voltage
3. Prevention of direct lightning attachment to underlying antennas
4. Bonding of antennas to surrounding structure
5. Use of in-service history to show the low likelihood of significant damage to an antenna and/or an upset or failure to the system caused by direct lightning attachment to the specified antenna or its associated parts
6. Use of anti-static coatings.

Antenna components are protected against the potential adverse effects from lightning attachment in several ways. Ineffective protection can result in damaged antenna components. Antennas have different roles in providing information, location and communication links for the aircraft. Not all antennas are treated with equal emphasis in the design of an aircraft integrated system. Some antennas are not critical to the mission and some are critical. For the criticality assessment, the designer is required to discuss the potential of an antenna failure with the certification leadership on the aircraft development project. Though it may be more effective to impose the same continued airworthiness requirements on all antennas, it may not be necessary. Careful observation of the antenna design process and specific installation criteria for transferring lightning current from antenna to the aircraft is necessary to prepare for the continued airworthiness design assessment.

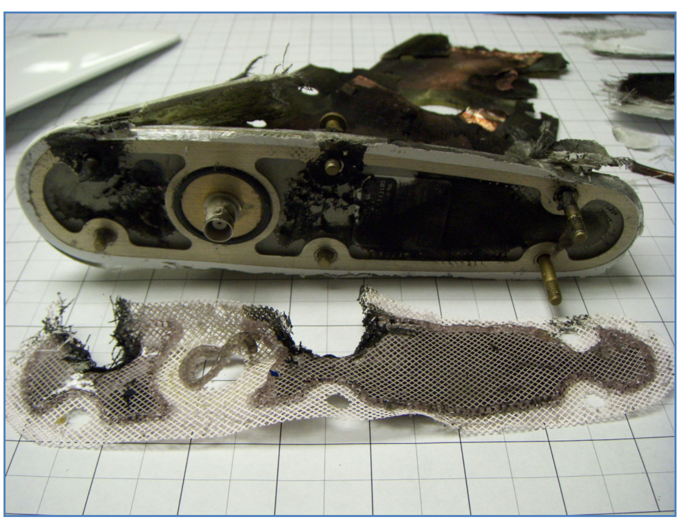


Figure 5-21 Antenna Direct Lightning Attachment Effect

Antennas can be adversely affected when lightning attachment occurs. Figure 5-21 shows an antenna disassembled after simulated lightning strike was applied to the antenna cover. The antenna shape and physical installation details are part of the lightning protection design. Protection methods used in these case study designs is one or more of the following methods:

A. Antennas inherently protected from direct lightning attachment by virtue of their location and geometry. The manufacturer in-service history has shown that low profile antennas mounted on the fuselage have a very low likelihood of direct lightning attachment
B. The antenna covering is able to withstand a zone 1A direct lightning strike with only minimal damage
C. The antenna covering is able to withstand a zone 2A direct lightning strike with only minimal damage and be able to function to its specified parameters
D. Antennas located in the nose and fin radome are protected from direct lightning attachment by metal diverter strips that divert direct lightning currents to structure. Segmented diverter strips are used on certain antennas to prevent lightning attachment to underlying antenna components.
E. Select antennas, those that are mounted on the fuselage, may be electrically bonded to structure to reduce the amount of conducted currents on the outer coax shield to an acceptable level in the event of a direct lightning attachment to the antenna. The bond is achieved either by a fay surface bond or through the mounting fasteners.
F. Inherent protection from surrounding metal structure
G. As an option for customers to select, the SATCOM low and high gain antennas incorporate segmented button diverter strips to prevent puncture to the underlying antenna elements.

The following Table 5-11 and Table 5-12 describe the navigation and communication installations and associated **protection** methods.

Antenna	Antenna Type	Antenna Geometry	Lightning Provisions	Protection Methods
Very High Frequency Comm.	Blade	Foot print area (retained sq. inches. Blade (retained inches from skin	Antenna base fay surface bonded to fuselage skin	The antenna shell proven to be adequate. Antenna's mounted on the fuselage area electrically bonded to structure. The bond is achieved either by a fay surface bond or thorough the mounting fasteners.
Glideslope, Weather Radar, Localizer	Structurally mounted array and loop inside radome	Inside Radome	Antennas attached to structure	Antennas located in the nose and fin radome are protected from direct lightning attachment by metal diverter strips that divert direct lightning currents to structure. Segmented diverter strips are also used on certain antennas to prevent lightning attachment to underlying antenna components.
Traffic Alert and Collision Avoidance System	Blister shaped	Food print area (retained) sq. inches, height (retained) inch from fuselage skin	Antenna base fay surface bonded to fuselage skin	Antennas inherently protected from direct lightning attachment by virtue of their location and geometry. Aircraft manufacturer in-service history has shown that low profile antennas mounted on the fuselage have a very low likelihood of direct lightning attachment. Antennas mounted on the fuselage are electrically bonded to structure. The bond is achieved either by a fay surface bond or through the mounting fasteners.
Air Traffic Control	Low Profile Blade	Foot prints area (retained) sq. inches, height (retained) inches from fuselage skin	Antenna base fay surface bonded to fuselage skin	Antennas inherently protected from direct lightning attachment by virtue of their location and geometry. Aircraft manufacturer in-service history has shown that low profile antennas mounted on the fuselage have a very low likelihood of direct lightning attachment. Antenna covering is able to withstand a direct lightning strike

Antenna	Antenna Type	Antenna Geometry	Lightning Provisions	Protection Methods
				with only minimal damage and be able to function to its specified parameters. Antennas mounted on the fuselage are electrically bonded to structure. The bond is achieved either by a fay surface bond or through the mounting fasteners.
Radio Altimeter	Conformal patch slightly above skin	Foot prints area (retained) sq. inches, height (retained) inches from fuselage skin	Antenna base fay surface bonded to fuselage skin	Antennas inherently protected from direct lightning attachment by virtue of their location and geometry. Aircraft manufacturer in-service history has shown that low profile antennas mounted on the fuselage have a very low likelihood of direct lightning attachment. Antennas mounted on the fuselage are electrically bonded to structure. The bond is achieved either by a fay surface bond or through the mounting fasteners.
Distance Measuring Equipment	Low Profile Blade	Foot prints area (retained) sq. inches, height (retained) inches from fuselage skin	Antenna base fay surface bonded to keel beam panel	Antennas inherently protected from direct lightning attachment by virtue of their location and geometry. Aircraft manufacturer in-service history has shown that low profile antennas mounted on the fuselage have a very low likelihood of direct lightning attachment. Antenna covering is able to withstand a direct lightning strike with only minimal damage and be able to function to its specified parameters. Antennas mounted on the fuselage are electrically bonded to structure. The bond is achieved either by a fay surface bond or through the mounting fasteners.

Table 5-11 Antenna physical installation design protection methods

Antenna	Antenna Type	Antenna Geometry	Lightning Provisions	Protection Methods
SATCOM	Low Profile Blade	Foot prints area (retained) sq. inches, low profile blade, height (retained) inches from fuselage skin with segmented diverted strips on crown of antenna placed perpendicular to the centerline	Antenna base fay surface bonded to fuselage skin with the segmented strips bonded to structure.	Antennas inherently protected from direct lightning attachment by virtue of their location and geometry. Aircraft manufacturer in-service history has shown that low profile antennas mounted on the fuselage have a very low likelihood of direct lightning attachment. Antennas mounted on the fuselage are electrically bonded to structure. The bond is achieved either by a fay surface bond or through the mounting fasteners. As an option, antenna incorporates segmented button diverter strips to prevent puncture to the underlying antenna elements.
Global Positioning System	Conformal panel slightly above skin	Foot prints area (retained) sq. inches, low profile blade, height (retained) inches from fuselage skin.	Antenna base fay surface bonded to fuselage skin	Similarity to existing lightning protection design method in use on existing OEM airplanes. Note: A review of specified airplanes lightning strike history was used to validate similar lightning protection design methods for both structural and fuel components implemented on this design.
Emergency Locator Transmitter	Low Profile Blade	Foot prints area (retained) sq. inches, low profile blade, height (retained) inches from	Antenna base fay surface bonded to fuselage skin.	Antennas inherently protected from direct lightning attachment by virtue of their location and geometry. Aircraft manufacturer in-service history has shown that low profile antennas mounted on the fuselage have a very low likelihood of direct lightning attachment. Antennas mounted on the fuselage are electrically bonded to

Antenna	Antenna Type	Antenna Geometry	Lightning Provisions	Protection Methods
		fuselage skin.		structure. The bond is achieved either by a fay surface bond or through the mounting fasteners.
High Frequency Radio	Slot antenna with fiberglass window	Installed within surrounding metal structure.	Leading edge is inherently bonded to airplane structure.	Antennas inherently protected from direct lightning attachment by virtue of their location and geometry. Aircraft manufacturer in-service history has shown that low profile antennas mounted on the fuselage have a very low likelihood of direct lightning attachment. Inherent protection from surrounding metal structure.
VHF Omni-range (VOR) Navigation System	Fiberglass Radome	Mounted under a fiberglass radome with aluminum diverter strip mounted on the centerline.	Diverter strip bonded at both ends to structure.	Antennas inherently protected from direct lightning attachment by virtue of their location and geometry. Aircraft manufacturer in-service history has shown that low profile antennas mounted on the fuselage have a very low likelihood of direct lightning attachment.
Marker Beacon	Low Profile Blade	Foot prints area (retained) sq. inches, low profile blade, height (retained) inches from fuselage skin.	Antenna base is fay surface bonded to keel beam panel	Antennas inherently protected from direct lightning attachment by virtue of their location and geometry. Aircraft manufacturer in-service history has shown that low profile antennas mounted on the fuselage have a very low likelihood of direct lightning attachment. Antennas mounted on the fuselage are electrically bonded to structure. The bond is achieved either by a fay surface bond or through the mounting fasteners.

Table 5-12 Antenna physical installation design protection methods

The antenna testing is part of the lightning protection design and certification. Means of compliance is gained in one or more of three different ways.

1. Qualification on production parts
2. Similarity to past qualification testing conducted on past production airplane
3. Similarity to existing lightning protection design method in use on existing OEM airplanes. Note: A review of specified airplanes in-service lightning strike history was used to validate similar lightning protection design methods for both structural and fuel components implemented on the this design.

The following Tables 5-13 and 5-14 describe the navigation and communication antenna installation **test** methods.

Antenna	Antenna Type	Antenna Geometry	Lightning Provisions	Protection Methods
Very High Frequency Communication	Blade	Foot print area (retained) inches, Blade (retained) from skin	Antenna base fay surface bonded to fuselage skin	1. Similarity to past qualification testing conducted on past production airplane. 2. Similarity to existing lightning protection design method in use on existing OEM airplanes. Note: A review of specified airplanes in-service lightning strike history was used to validate similar lightning protection design methods for both structural and fuel components implemented on this design.
Glideslope, Weather Radar, Localizer	Structurally mounted array and loop inside radome	Inside radome	Antennas attached to structure	2. Similarity to existing lightning protection design method in use on existing OEM airplanes. Note: A review of specified airplanes in-service lightning strike history was used to validate similar lightning protection design methods for both structural and fuel components implemented on this design.
Traffic Alert and Collision Avoidance System	Blister shaped	Foot print area (retained) sq. inches, height (retained) inch from fuselage	Antenna base fay surface bonded to fuselage skin	2. Similarity to existing lightning protection design method in use on existing OEM airplanes. Note: A review of specified airplanes in-service lightning strike history was used to validate similar lightning protection design methods for both structural and fuel components implemented on this design.

Antenna	Antenna Type	Antenna Geometry	Lightning Provisions	Protection Methods
		skin		
Air Traffic Control	Low Profile Blade	Foot print area (retained) sq. inches, height (retained) inches from fuselage skin	Antenna base fay surface bonded to fuselage skin	1. Similarity to past qualification testing conducted on past production airplane. 2. Similarity to existing lightning protection design method in use on existing OEM airplanes. Note: A review of specified airplanes in-service lightning strike history was used to validate similar lightning protection design methods for both structural and fuel components implemented on this design.
Radio Altimeter	Conformal patch slightly above skin	Foot print area (retained) sq.. inches, height (retained) inch from fuselage skin	Antenna base fay surface bonded to fuselage skin	2. Similarity to existing lightning protection design method in use on existing OEM airplanes. Note: A review of specified airplanes in-service lightning strike history was used to validate similar lightning protection design methods for both structural and fuel components implemented on this design.
Distance Measuring Equipment	Low Profile Blade	Foot print area (retained) sq. inches, height (retained) inches from fuselage skin	Antenna base fay surface bonded to keel beam panel	1. Similarity to past qualification testing conducted on past production airplane. 2. Similarity to existing lightning protection design method in use on existing OEM airplanes. Note: A review of specified airplanes in-service lightning strike history was used to validate similar lightning protection design methods for both structural and fuel components implemented on this design.

Table 5-13 Antenna physical installation design test methods (specific tests, dates, and aircraft models removed from this table)

Antenna	Antenna Type	Antenna Geometry	Lightning Provisions	Protection Methods
SATCOM	Low Profile Blade	Foot print area (retained) sq., inches, low profile blade, height (retained) inches from fuselage skin with segmented diverter strips on crown of antenna placed perpendicular to the centerline	Antenna base fay surface bonded to fuselage skin with the segmented strips bonded to structure	1. Similarity to past qualification testing conducted on past production airplane. 2. Similarity to existing lightning protection design method in use on existing OEM airplanes. Note: A review of specified airplanes in-service lightning strike history was used to validate similar lightning protection design methods for both structural and fuel components implemented on this design.
Global Positioning System	Conformal panel slightly above skin	Foot prints area (retained) sq. inches, height (retained) inches from fuselage skin	Antenna base fay surface bonded to fuselage skin	2. Similarity to existing lightning protection design method in use on existing OEM airplanes. Note: A review of specified airplanes in-service lightning strike history was used to validate similar lightning protection design methods for both structural and fuel components implemented on this design.
Emergency Locator Transmitter	Low Profile Blade	Foot prints area (retained) sq. inches, height (retained) inches from fuselage skin	Antenna base fay surface bonded to fuselage skin	2. Similarity to existing lightning protection design method in use on existing OEM airplanes. Note: A review of specified airplanes in-service lightning strike history was used to validate similar lightning protection design methods for both structural and fuel components implemented on this design.

Antenna	Antenna Type	Antenna Geometry	Lightning Provisions	Protection Methods
High Frequency Radio	Slot antenna with fiberglass window	Installed within surrounding metal structure	Leading edge is inherently bonded to airplane structure	2. Similarity to existing lightning protection design method in use on existing OEM airplanes. Note: A review of specified airplanes in-service lightning strike history was used to validate similar lightning protection design methods for both structural and fuel components implemented on this design.
VHF Omni-range Navigation System	Fiberglass radome	Mounted under a fiberglass radome with aluminum diverter strip mounted on the centerline	Diverter strip bonded at both ends to structure	1. Similarity to past qualification testing conducted on past production airplane. 2. Similarity to existing lightning protection design method in use on existing OEM airplanes. Note: A review of specified airplanes in-service lightning strike history was used to validate similar lightning protection design methods for both structural and fuel components implemented on this design.
Marker Beacon	Low Profile Blade	Foot prints area (retained) sq. inches, height (retained) inches from fuselage skin	Antenna base is fay surface bonded to keel beam panel	2. Similarity to existing lightning protection design method in use on existing OEM airplanes. Note: A review of specified airplanes in-service lightning strike history was used to validate similar lightning protection design methods for both structural and fuel components implemented on this design.

Table 5-14 Antenna physical installation design test methods (specific tests, dates, and aircraft models removed from this table)

Lightning Protection of Antennas

Lightning protection components that protect antennas from the potentially adverse effects of lightning strikes are listed in the following paragraphs. Specific protection features for antenna components have been added to various antennas droning the design phase to prevent damage to communication and navigation systems, minimize damage to the antennas and eliminate any safety hazards associated with lightning currents on the antenna's wiring.

Communication and Navigation Systems Protection - The acceptable loss or upset of these systems in the event of exposure to direct lightning attachment is dependent on its critical failure mode during a direct lightning event. For the (aircraft types retained) aircrafts the ILS (Glideslope and Localizer) and RA systems have a critical failure mode of undetectable erroneous data to the flight crew generated from the system in the event of a direct lightning attachment to the system's antennas. Whether the system receives erroneous data is dependent on the architecture and the damage to the antenna. For example, complete destruction of the antenna (ILS case) or set of antennas (RA case) would disable the system and would not pose a threat to the airplane. The concern is if the functionality of the ILS antenna or set of RA antennas is degraded to a point where the antennas corrupt the received signals and the system interprets these signals as valid data. For this to happen, the following sequence of events would have to occur (unique for each system).

The Radio Altimeter lightning event- A direct lightning attachment occurs to the nose and sweeps back in the vicinity of the RA set of antennas. Since all RA antennas are in-line (fore to aft) it is remotely possible for lightning to attach to all four antennas in a single event. Direct attachment would have to occur to the antenna element itself. The antenna element is a printed circuit board with (thickness retained) of copper on top covered with primer and environmental paint cover. In order for direct attachment to occur, the voltage between the heel of the sweeping lightning arc and the antenna element would have to be high enough to puncture the paint cover. Since the RA antenna dimension is approximately (retained measure) inches long, the likelihood of puncture of multiple antennas during a single event is remote.

The amount of energy in the direct lightning attachment to the antenna element would have to be small enough to degrade the receive antennas, not completely destroy the element. Based on statistical data reported in [1] AC20-53A, “Protection of Airplane Fuel Systems Against Fuel Vapor Ignition Due to Lightning, dated 4-12-85 and (document reference retained), (aircraft type reference applicability retained) Fuel System Description and Analysis Document", 99% of lightning strokes in the continuing stroke phase are above 30 amps. With the minimum dwell time of a sweeping arc on painted aluminum being about 5ms (industry accepted value, non-proprietary), the energy deposited into the antenna element exceeds the amount of energy required to vaporize the entire RA antenna element, rendering the antenna useless. The likelihood of a direct attachment depositing these low energy levels is remote. This is assuming a re-attachment to the antenna element would occur during the low-level continuing current phase which again is unlikely.

The ILS (Glideslope and Localizer) Lightning Event

A protection system for the ILS antennas has been implemented but is only an option. However, due to nose radome interchangeability and reduced risk of damage to the weather radar, all (aircraft type's reference retained) radomes will have diverter strips installed. Since the ILS protection system (i.e. diverter strips) is only an option the following scenario is presented to describe the inherent protection without the diverter strips on the radome causing a direct attachment to either the Glideslope or Localizer antenna. Based on past history, radomes without diverter strips have an increased rate of damage associated with lightning puncturing the radome and attaching to the weather radar. The position and geometry of the weather radar with respect to the ILS antennas "shadows" these antennas from direct lightning attachment. This concept is proven based on the lack of damage or upset in-service reports (for the entire manufacturer's fleet) to the Glideslope or Localizer antennas or the system associated with direct lightning attachment. A direct lightning attachment to either of these antennas is considered remote. As in the RA scenario, the energy level deposited to the antenna would have to be low enough to just cripple the antenna, not completely destroy it. The likelihood of this is unknown but considered very low.

Based on this analysis, the likelihood of undetectable erroneous data from both Radio Altimeter and ILS systems associated with the direct effects of lightning is acceptably small as determined by the design.

Communication and navigation systems performing essential or nonessential functions have no critical failure modes. Therefore, the upset or failure of these systems or a subset of these systems when the antennas are exposed to the direct effects of lightning is acceptable. Various protection measures for these systems have been implemented to reduce damage and maintenance to these systems. Antennas are protected so that lightning damage to associated electronic equipment is minimized. One or more of the following approaches to antenna protection is used to protect the antennas (each approach has successful in-service records).

a. Location in a shielded area
b. Direct grounding of the antenna element to structure
c. Diverter strips that conduct stroke currents to ground.

Verification of antenna protection is performed during the certification of each design by comparison to previous designs, test, and/or analysis. Table's 5-11, 5-12, 5-13, and 5-14 detail the location of antennas, protection method, and verification method. The testing associated with direct effects of the lightning protection for the antennas is listed below. The design methods used on the (specific aircraft reference retained) for direct effects lightning protection of antennas include one or a combination thereof of several lightning protection techniques such as diverter strips, antenna attachment conductive gaskets and bond straps strategically placed to provide a bond path from the antenna radome to the aircraft structure.

Some antennas are inherently protected from direct lightning attachment by virtue of their location and geometry. OEM in-service history has shown that low profile antennas mounted on the fuselage have a very low likelihood of direct lightning attachment. For antennas deployed in lightning Zone 1, the antennas are equipped with protective covering that is able to withstand a Zone 1A direct lightning strike with only minimal damage. For antennas deployed in lightning Zone 2, the antennas are equipped with a protective that is able to withstand a Zone 2A direct lightning strike with only minimal damage and be able to function to its specified parameters. For antennas located in the nose and fin radome, protection is provided to withstand a direct lightning attachment by metal diverter strips that divert direct lightning currents to structure. Segmented diverter strips are also used on certain antennas to prevent lightning attachment to underlying antenna components. Select antennas, those that are mounted on the fuselage, are electrically bonded to structure to reduce the amount of conducted currents on the outer coax shield to an acceptable level in the event of a direct lightning attachment to the antenna. The bond is achieved either by a fay surface bond or through the mounting fasteners. Most antennas use the inherent protection from surrounding metal structure. As an option, the SATCOM low and high gain antennas incorporate segmented button diverter strips to prevent puncture to the underlying antenna elements.

5.7.4 Case Studies for Structures Direct Effects Protection

These case study exercises will utilize assessment sheets to demonstrate the methodology. The structural lightning protection components that have been selected to demonstrate the methodology contained in this thesis are as follows:

1. Nose Radome lightning protection - Diverter Strips
2. Empennage VOR Antenna lightning protection - antenna cap diverters
3. Rudder lightning protection – rudder tip and trailing edge diverter strips

Case Studies for Structural Lightning Protection Components

This selection of mechanical protection to aircraft structure covers the most common lightning protection schemes used in the industry.

Part 1: Structural protection of Nose Radome General Description

Protection of antenna radomes are often accomplished with both diverter strips of metallic material mounted to the outside of the radome and also earthing wires used as a path for lightning current to travel safely without damaging installations during a lightning strike event. Protection is also provided to structural extremities where lightning strikes may cause damage to the control surface. For the example demonstrated in this work, the rudder tip and trailing edges were examined. Often the trailing edges of structural control surfaces are made of composite materials. These examples provide a way forward for testing the methodology in a test case associated with composite structure protection. Composite structural components in Figure 5-22 and Figure 5-23 require specific protection designs that are tested, qualified and approved for application to the aircraft in these studies. Data was gathered from these tests to exercise the methodology and demonstrate how the methodology would work if used in an aircraft design program. The shaded areas depicted in Figure 5-22 and Figure 5-23 represents the composite structures applications on the aircraft under study.

Proprietary Graphic Retained

Figure 5-22 Composite Structural Members (Top View)

Note: Details of aircraft composite structural applications Proprietary Appendix to protect the proprietary nature of the information.

Proprietary Graphic Retained

Figure 5-23 Composite Structural Members (Top View)

Note: Details of aircraft composite structural applications Proprietary Appendix to protect the proprietary nature of the information.

Case Study 1 Structural Protection – Nose Radome Case Study and Assessment Sheet

Engineering L/HIRF Protective Device Assessment Sheet Protection Component Name

Nose Radome Lightning Diverter Strips

Section 1. Lightning/HIRF Protection Component Data	
Assessment Sheet Number	STR001 (STR=Structures, FUL=Fuel, SYS=Systems, ANT=Antenna)
Engineer Name:	Bill Wright
Part Number:	P/N XYZ (part number retained to protect proprietary data)
Manufacturer:	Lightning Diverter Inc.
Lightning Zone	Zone 1
Design Service Life Goal:	Design for life of aircraft. No overhaul required.
Date:	September 12, 2009

Section 2. Component Description
System Criticality: Critical **Description:** Lightning diverter strips are installed on the aircraft nose radome. The airplane shall be designed so that direct attachment to antennas, control surfaces, radomes, or any other exposed systems will not result in a failure due to a lightning strike leading to a potentially Catastrophic condition. The nose radome shall have protection against a lightning strike per the aircraft Lightning Zoning Diagram so that a lightning strike will not cause damage to the nose radome or systems that it protects. The diverter strips are installed to minimize the possibility of punch through the radome structure or create debris which could adversely affect the safety of the aircraft. Bonding clips attached to the edge of the radome are used to bond each diverter strip to the aircraft structure. Design requirement: The nose radome shall have externally mounted lightning diverter strips or bus bars that are electrically grounded to the bulkhead through clips with a bonding resistance

value of less-than-or-equal-to (<=) XYZ milliohms (impedance value retained).

Assumption and Rationale for the specification of this protection (manufacturer specification number retained to protect proprietary data): This provides lightning protection to systems underneath the radome (such as the Weather Radar Antenna Unit and landing system)

Section 3. Component Purpose and Operational Theory

An installation of permanent lightning diverter rods is available for the aircraft nose radome. At the customers' option, diverter rods may be installed which will prevent radome lightning damage from a large majority of strikes to the nose radome area. Without the diverter rods, the high potential and large current associated with a stroke can cause penetration of the fiberglass radome with possible severe damage to the radome and to the antennas within It.

Although the airplane can fly with a damaged radome, the diverter rods can reduce maintenance cost. A high percentage of strokes to the aircraft will be to the nose. Without the diverter rods the radome will be damaged by most of the nose-strikes. The radome will be protected from strokes up to 200,000 amperes (common industry accepted value) when the diverter rods are used.

The lightning protection system for the aircraft nose radome is similar to that used on two other previously deigned aircraft (aircraft types retained to protect proprietary data). Damage from strikes on the nose should be confined to locally burn decorative paint and slight erosion of metal from the diverter rod.

Section 4. Component Schematic and Installation Details

Installation Details:

A group of several diverter rods are located about the radome exterior so that regardless of the orientation of the radar antenna, the lightning discharge will flash over the radome surface without puncturing It. The diverter rods are constructed of a specified material (material specification retained to protect proprietary data) of approximately XYZ circular mils cross-section (material size retained to protect proprietary data), so that they are capable of withstanding several strokes.

Bond Path Providing Protection:

The bond path for the diverter strips is from initial lightning attachment to the diverter, through fastening hardware on the diverter to the surround band on the radome to an earthing ground strap from the surround band to the aircraft primary structure.

The radome diverter strips protect against the attachment of lightning to underlying components.

The lightning protection consists of metal diverter strips attached to metal conductor straps of the same type material; with the metal conductor straps (actual material for each component mentioned is retained to protect proprietary data) cemented to the composite radome with all-purpose epoxy. This is a controlled interface that requires no more than XYZ ohms (impedance requirement retained to protect proprietary data) between diverter strips and the conductor straps.

The solid metal bus bars (diverter strips) with a prepared finish (material and finish retained to protect proprietary data) are mounted to a composite domed structure. The diverter strips are attached with multiple fasteners. The fastening system includes metal screws and nylon threaded potted inserts (material and finish of screws retained to protect proprietary data).

The most aft fastener on the diverter strips electrically bonds the diverter strips to the metal ground band (mounted on the radome); the bond path from the diverter strips to the ground band consists of a metal screw, with a prepared finish metal grounding bushing and doubler, a metal washer, and metal nut. After installation, the joint is sealed with a specified sealant (or equivalent). Note: Material, finish and specific sealant used on mounting hardware is retained to protect proprietary data.

The first metal ground band (on the solid laminate skin on the aft edge of the composite dome) is mounted using a metal bolt with a corrosion protective finish (metal and finish retained to protect proprietary data) to mate assemblies and metal self-locking nut per manufacturer specification which are wet installed with a specified sealant. These fasteners are only conductive when installed in a controlled interference fit (~ XYZ inches) environment where the corrosion protective coating is expected to shear off and provide an adequate electrical bond. Note: all finish, material and sealant call outs along with specification numbers retained to protection proprietary data.

The composite domed structure is attached to the forward metallic pressure ground band with eight metallic latches mounted to the radome and eight keepers mounted to the forward pressure bulkhead ground band. The latches and keepers are mounted with metal bolts, metal washers, and metal nuts using specific manufacturer specified (or equivalent) sealant. Note: specific material and finish of hardware and sealants retained to protect proprietary data.

The metal bulkhead brackets create a bond path between the forward pressure bulkhead ground band and primary structure; they are installed using sealant with multiple metal rivets per the specific manufacturer bonding and earthing requirements, using specified sealant (or equivalent). The installation is fillet sealed with a specified sealant (or equivalent). Note all specification and materials retained to protect proprietary data.

The metal radome brackets are wet installed using a manufacturer specified process and material surface bond and mounted to the ground band of the composite domed structure with metal bolts and metal collars using a specified manufacturer sealant (or equivalent). Note all specification and materials retained to protect proprietary data.

The metal spring clips are wet installed using a manufacturer specified process surface bond and mounted to the primary structure on the metal forward pressure dome ground band with metal bolts and metal collars using a specific manufacturer proposed sealant (or equivalent). Note: all specification and materials retained to protect proprietary data.

A typical radome configuration includes a radome attached to the aircraft with hinges like the one in the picture below. Many radome installation designs do not rely on the hinges to transfer the lightning current since the current is large and can weld the hinges in place if the hinges are the only path for the current to transfer to the aircraft primary structure during a lightning event. In this aircraft design spring clips are used to attach the radome diverter strips to primary structure through the ground band in multiple places circumferentially around the dome.

Bond Path Description:

1. Diverter strip to multiple radome ground bands
2. Radome ground bands are glued to the radome

Note: Fasteners attach the diverter strips to ground bands

3. Most aft ground band is electrically connected to the diverter strip through a fastener
4. Forward ground band is attached to eight latches mounted to the radome
5. Eight latches on the radome attach to eight keepers
6. Eight keepers are mounted on the forward pressure bulkhead ground band
7. Forward pressure bulkhead ground band is attached to eight brackets
8. Eight brackets are attached to the forward pressure bulkhead
9. Forward pressure bulkhead is attached to primary structure of the aircraft fuselage

A detailed review of the material and finish interfaces was completed. Mounting hardware associated with bond path is found to be compatible and properly sealed by this analysis sheet evaluation of material and finish compatibilities.

Section 5. Installation Environmental Threats

The diverter strip installations are outside the aircraft pressure vessel and exposed to multiple environmental threats. To protect against these threats and ensure availability of a continued adequate bond path without undesirable impedance degradation, appropriate protection of materials and installations is applied as reviewed by this assessment.

Description of installed environment:

This installation is outside pressure vessel and exposed to severe temperature changes, contamination, and erosion from particulates, damage from hail or other objects impinging on the nose of the aircraft during flight.

Flammable Leakage Zone Description and Protection:

This installation of lightning protection is not mounted in a flammable leakage zone.

Ratings of environmental threats:

Location: Nose Radome Exterior		
Threat Type	**Rating of threat**	**Installation resistance to**

	severity in this location (High, Medium, Low)	degradation (High Medium, Low)
System Operating Fluids (oil, hydraulic fluid, Grease and Lubricants)	Low	High
Chemicals and Applied Fluids (cleaning fluids, fire retardants, de-icing, wing anti-ice fluids, liquid cooling)	Medium	High
Natural Occurring Fluids (condensation, precipitation, humidity, ice, rain, snow)	High	High
Temperature Exposure (swings in temperature, and extensive exposure to extreme high or low temperatures)	Medium	High
Vibration (low or high frequency vibration)	Medium	High
Fuel (Exposure to fuel)	None	High
Flammable Leakage Zone (Yes/No)	None	High

Section 6. Assessment of Critical Characteristics in the Installed Environment

The continued airworthiness of associated components within the lightning protection designed bond path is expected to last the life of the installation on the aircraft. The radome has been designed to withstand accidental impact damage. Damage will only occur as a result of accidental physical impact or severe lightning strike that would be evident to the operating crew. Service experience is expected to be similar to other aircraft radome installation designs. All fasteners are installed with sealant and interfaces between fay surface components such as the bulkhead brackets and ground bands also include sealants in the interfaces that prevent moisture ingress and potential subsequent corrosion. Fasteners are coated with corrosion inhibiting compound to prevent unexpected corrosion and resulting impedance increases within the lightning electrical bond path. Fastener installations are similar to installations in many designs previously installed on other models by this manufacturer and have proven successful performance.

Section 7. Test Plan Input

The effectiveness of the radome protection system and its effect on antenna efficiency has been checked in the laboratory. Qualification testing included specific lightning diverter placement to ensure most effective lightning damage mitigation while also maintaining good antenna communication capability behind the radome installation. In addition, the radome was struck by simulated lightning after a specified number of hours (number of hours retained to protect

proprietary data) exposure to salt spray (the minimum required by Specification DO-160). Radomes with metal diverter strips perform well in-service to protect the underlying systems from damage. The radome and diverter strips perform their intended function well, but can be damaged when struck by lightning. Post lightning strike inspections ensure the diverter strips are intact and functional. It is expected that the laboratory testing for the specific radome configuration under test include adequate environmental threat applied to the radome with diverters installed to prove the radome protection will be adequately available throughout the life of the installed parts. If additional input is required for the continued airworthiness engineer, please contact the lead engineer noted at the top of this assessment for clarification.	
Section 8. Test Data Results	
The effectiveness of the radome protection system and its effect on antenna efficiency has been checked in the laboratory. Tests with simulated lightning have shown that the aircraft radome which is the same size and shape as two other aircraft designed and produced by this manufacturer, is adequately protected with four diverters as shown in previous designs on another aircraft produced by this manufacture. A number of rods are used to allow for possible deterioration of radome dielectric strength. The permanent diverter strips do not degrade the radome performance below that recommended for Radomes. Qualification testing included: 1. Qualification testing to validate the lightning performance of the radome to include peak kA, number of strips, and placement of strips 2. The structural qualification test procedure covers bird strike, hail, chemicals, salt spray, etc. 3. Electrical qualification testing. All qualification testing was completed to the satisfaction of the test lab and the radome is expected to be certifiable upon review by regulatory authorities of the qualification test results and threat levels.	
Section 9. Report from Test Engineer Regarding on Continued Airworthiness	
Test Engineer Name:	Robert Crumb
Report: **(include significant findings and relevance to continued airworthiness)**	**Lightning strike diversion effectiveness and diverter security of attachment to Radome:** Investigation was conducted to prevent moisture ingression into the aircraft nose radome. Moisture may enter the honeycomb core either through the multiple ply fiberglass/epoxy face sheet, fastener penetrations for the lightning diverter strips or in-service repairs. The subject of this evaluation is the current and alternative methods of preventing moisture at the fastener locations. The lightning diverter strips are fastened to the exterior of the radome by fastening to a non-

	conductive material. The non-conductive inserts are sealed and bonded per the aircraft manufacturer specification (specification retained to protect proprietary data). The manufacturer specification states that the drawing must specify a primer for it to be a required part of the fabrication procedure. The specified primer enhances the bond of the sealant to many substrates. Conclusion for diverter strip attachment: 1. The sealant that provides the best bond to the non-conductive insert was a manufacturer specification sealant and primer. High torque loads relative to the other methods and cohesive failure modes were achieved. This performance was significantly degraded by not applying the specified primer. 2. The manufacturer specified sealant did not adhere to the non-conductive insert with either of the conditions evaluated. The failure torque load was low and highly variable. 3. Because the manufacturer specified process bonds to the non-conductive material, it provides a barrier to moisture penetration after the sealant that is bonded to the core. The relative quality of the manufacturer specified sealant seal versus another manufacturer specified sealant type seal is unknown under production conditions. In the production environment, both sealants are vulnerable to incomplete filling due to operator workmanship. However, the lower viscosity of the sealant may help ensure uniformity. 4. A possible feature of the poor adhesion of alternative sealant specification is that it makes it easier for airlines to remove and replace the lightning diverter strips.

Section 10. Design Revision Request
None
Section 11. Revision accepted by Program
N/A
Section 12. Description of Final Optimized Design
Action Taken: Report posted with change to specified sealant and process.
The design of the radome lightning protection diverters has been determined to be acceptable for installation on the aircraft with one specific revision to the tested design. The use of sealant in the fastener interface to the radome diverter to ensure that moisture does not ingress into the

radome-to-diverter interface and cause an increase of the lightning bond path resistance is highly recommended to be the manufacturer recommendations for this test using a specific referenced primer. This sealant has been shown to perform best for the application. Deviations within the design from this recommendation are requested to be sent to the attention of the lightning protection continued airworthiness assessment engineering group.	
Approval:	
Mr. G. Sweers, Lightning Protection Analyst	Original Signed
Mr. Keith Smith, Lightning Protection Designer	Original Signed
Mr. Jacob Owen, Bonding and Earthing Engineer	Original Signed
Mr. John Taylor, Chief Engineer	Original Signed

Figures attached to Assessment Sheet for Nose Radome Installation

The following graphics are collected for use in the assessment of the lightning protection. These graphics were used to identify key component attributes contained within the assessment sheets.

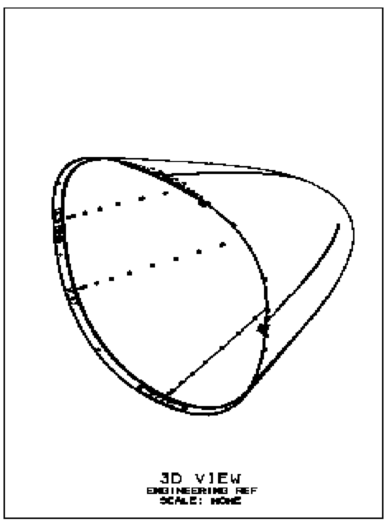


Figure 5-24 Radome 3-D View and general orientation

Proprietary Graphic Retained

Figure 5-25 Radome dimensions and diverter strip locator

Proprietary Graphic Retained

Figure 5-26 Radome diverter strip fastener locations

Proprietary Graphic Retained

Figure 5-27 Radome bond jumper installation detail and location

Proprietary Graphic Retained

Figure 5-28 Radome diverter strip installation detail and specifications

Proprietary Graphic Retained

Figure 5-29 Radome diverter strip length and part number

Proprietary Graphic Retained

Figure 5-30 Radome diverter strip blind fastener installation

Proprietary Graphic Retained

Figure 5-31 Radome diverter strip length and part number

Structural Protection of Empennage General Description

The aircraft empennage contains several varieties of lightning protection components, all of which are in place to protect against the direct effects of lightning on the empennage structure with the exception of the VOR fin cap protection which is provided to protect the structural aspects of the VOR cap. The lightning protection is necessary to protect composite structural components used in the empennage control surfaces. Lightning protection consists of components listed in Figure 5-32 to protect the rudder, rudder tip and horizontal stabilizer tip.

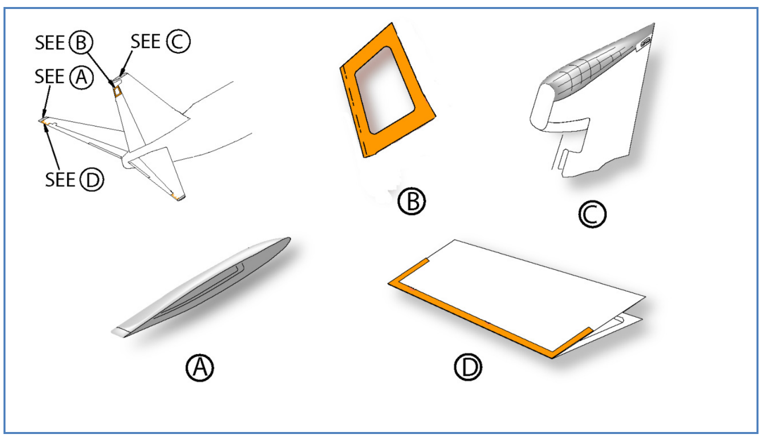


Figure 5-32 Empennage Structural Protection Components

A - Aluminum Mesh Protection on tips
B - Aluminum Strip Protection on rudder
C - Aluminum Mesh Protection on forward portion of rudder tip for VOR antenna
D - Aluminum Strip Protection on horizontal stabilizer

With the protection identified in Figure 5-32 in place, severe damage to structural components that make up the empennage flight control surfaces will minimize negative impact on the continued safe flight and landing of the aircraft.

Part 2: Structural Protection of Empennage VOR Antenna General Description

The VOR system has two VOR/marker beacon (VOR/MB) receivers. The receivers have VOR and marker beacon functions. The location of the VOR antenna installation is contained in Figure 5-33 depicted at the top of the rudder. The navigation (NAV) control panels give manual tune inputs to the VOR/MB receivers. There are two NAV control panels, one for the captain and one for the first officer. RF signals from the VOR/LOC antenna go to the VOR/MB receivers. The VOR/MB receivers use the RF signals to calculate station bearing and decode the Morse code station identifier signal and station audio. The receivers send VOR bearing to the remote magnetic indicator (RMI). You can select the RMI bearing pointers to show VOR or ADF station bearing with the RMI bearing pointer selectors. The receivers send VOR bearing data to the displays in the flight deck for display. The switches in the flight deck allow the crew to select VOR/MB receiver 1 or VOR/MB receiver 2 as the source for the captain and first officer displays.

Case Study 2 Structural Protection - Empennage VOR Antenna and Assessment Sheet

The VOR/LOC antenna is on the top of the vertical stabilizer. VOR/MB receiver 1 is on the aircraft equipment bay A shelf and VOR/MB receiver 2 is on the B shelf. The VOR/LOC antenna assembly is a fin cap type installed on top of the vertical stabilizer. The fin cap in Figure 5-34 shows the VOR antenna cap and Figure 5-35 shows the location of the diverter strip protection on the VOR fin cap. The antenna consists of two balanced half loops with a hybrid coupler added for increased reliability under fault conditions. The hybrid coupler is composed of two quarter wavelength lines with the dual outputs to the receivers shunted by a resistor. In addition, a tuning stub is connected to each half loop.

Engineering L/HIRF Protective Device Assessment Sheet Protection Component Name

VHF Omni-directional Ranging (VOR) System Antenna, VOR Fin Cap Antenna TYPE NO. DX

Section 1. Lightning/HIRF Protection Component Data	
Assessment Sheet Number	ANT001 (STR=Structures, FUL=Fuel, SYS=Systems, ANT=Antenna)
Engineer Name:	Bill Preston
Part Number:	NAC2123
Manufacturer:	Antenna Products and Technologies of New Jersey
Lightning Zone	Zone 1
Design Service Life Goal:	Design for life of aircraft. No overhaul required.
Date: November 12 2009	
Section 2. Component Description	
System Criticality: Critical	

Description:

The VHF Omni-directional Ranging (VOR) system is a navigation aid that gives magnetic bearing data from a VOR ground station to the airplane. The VOR/LOC antenna sends RF signals to the VOR/MB receivers inside the aircraft. The antenna installation is made up of an antenna radome mounted to the tip of the rudder using a number of leading edge fin type mounting screws. Under the radome are 2 RF type connectors attached to the antenna. Along the base of the antenna are a number of mounting screws. Several of the screws secure the trailing edge fin to the antenna. All mounting screws (Part number retained) are cadmium plated alloy steel self-locking. Screws are mounted using Cadmium plated alloy steel self-locking nut plates (Part number retained). The antenna mount is electrically bonded to the antenna. This interface is cleaned and prepared for an electrical bond upon installation of the antenna. The maximum resistance of the fay surface bond interface at the time of installation is X (resistance retained) ohms. A protective coating of corrosion preventive compound (Specification number retained) is applied to the mating surfaces of the airplane and the antenna structure. One manufacturer of this compound is produced by (Manufacturer information retained). The electrical bond is checked upon installation between antenna and airplane structure per (reference check retained). Resistance should not exceed (resistance value retained) ohms.

Section 3. Component Purpose and Operational Theory

Antenna Type (Part number retained) is intended for use with a VOR omni-range navigation receiver and localizer for instrument landings. It is designed to be installed as a tail fin cap for the aircraft. The (antenna type number retained) is approved under the manufacturer's part number (part number retained). The antenna installation consists of metallic leading and trailing edge fin tips mounted on a fiberglass shell to provide an aerodynamic surface for the fin cap.

The outline dimensions are shown in attached figures to this assessment.

Section 4. Component Schematic and Installation Details

For schematics, see drawings contained in the attached figures of this assessment.

Installation Details:

No repairs, other than replacement of the leading and trailing edges, can be made on the antenna. If damage or failure is noted, the antenna must be replaced. A damaged antenna may be returned to the manufacturer (Manufacturer name retained) for inspection and evaluation.

The antenna connectors and coaxial cables should be visually inspected for damage or unusual wear. All mating surfaces, including those between the antenna, the leading, and the trailing edges must be carefully fitted. Assemble the antenna by replacing the leading edge or trailing edge antenna cover, as applicable, on antenna assembly. Replace screws and tighten. The mounting screws (part numbers retained) are Cadmium-Plated alloy steel recessed head screws.

Bond Path Providing Protection:

1. The aluminum diverter strip is electrically connected to the aluminum sub-structure with two cadmium plated CRES fasteners and self-locking cadmium plated CRES nut plates.

2. The aluminum diverter strip is attached to the fiberglass radome with multiple sets of cadmium plated titanium bolts and cadmium plated CRES collars

3. VOR Radome is attached to the aircraft structure with cadmium coated titanium bolts and Cadmium plated Nut-plates

Mounting hardware is sealed upon installation.

Installation comment by reviewing engineer:

According to a review by this Assessment Sheet engineer the interface between the mounting hardware and the aluminum structure is completed with compatible metals.

Mounting hardware associated with bond path is found to be compatible and properly sealed.

Section 5. Installation Environmental Threats

The VOR antenna installation is outside the pressure vessel and exposed to multiple environmental threats.

Description of installed environment:

Installation is outside pressure vessel and exposed to severe temperature changes, contamination from airborne elements, and erosion from particulates, damage from hail or other objects impinging on the nose of the aircraft during flight.

Flammable Leakage Zone Description and Protection:

N/A

Ratings of environmental threats:

Location: Nose Radome Exterior		
Threat Type	**Rating of threat severity in this location (High, Medium, Low)**	**Installation resistance to degradation (High Medium, Low)**
System Operating Fluids (oil, hydraulic fluid, Grease and Lubricants)	Low	High
Chemicals and Applied Fluids (cleaning fluids, fire retardants, de-icing, wing anti-ice fluids, liquid cooling)	Medium	High
Natural Occurring Fluids (condensation, precipitation, humidity, ice, rain, snow)	High	High
Temperature Exposure (swings in temperature, and extensive exposure to extreme high or low temperatures)	High	High
Vibration (low or high frequency vibration)	Medium	High
Fuel (Exposure to fuel)	N/A	High
Flammable Leakage Zone (Yes/No)	N/A	High

Section 6. Assessment of Critical Characteristics in the Installed Environment

<table>
<tr><td colspan="2">According to the reviewing engineer, the continued airworthiness of associated components within the lightning protection designed bond path in this radome design is expected to last the life of the installation on the aircraft. The VOR antenna has been designed to withstand accidental impact damage. Damage will only occur as a result of accidental physical impact or severe lightning strike that would be evident to the operating crew due to antenna input errors or physical inspection of the dome after the lightning strike. Service experience is expected to be similar to other aircraft VOR antenna installation designs. All fasteners are installed with sealant. The interface between mating surface of the antenna and the structure is cleaned and a protective coating of corrosion prevention compound (compound reference retained) is applied between the two surfaces. This installation approach will prevent moisture ingress and potential subsequent corrosion. Fasteners are coated with cadmium; a corrosion inhibiting material to prevent unexpected corrosion that would result in impedance increases within the lightning electrical bond path. Fastener installations are similar to installations in many other aircraft models developed by this manufacturer that have demonstrated successful long-term performance.</td></tr>
<tr><td colspan="2">Section 7. Test Plan Input</td></tr>
<tr><td colspan="2">Testing for the interface between the antenna and structure shall be performed using moisture to simulate an antenna installation in a moist environment. Salt spray is an appropriate. This simulation shall test the resistance to corrosion of the antenna interface. Once moisture is applied over a period of (number of hours retained) hours or more, a test shall be conducted to ensure that the interface is within the (resistance value retained) Ohm resistance value required at the time of the original installation.</td></tr>
<tr><td colspan="2">Section 8. Test Data Results</td></tr>
<tr><td colspan="2">Tests for this installation have been accomplished by similarity to other past aircraft radome installation designs developed by this manufacturer. No new testing is required. Past performance results show resistance to the degradation associated with environmental threats and associated replacements of this antenna radome after lightning strike direct effect damage. Continued good performance of the lightning protection associated with the VOR antenna radome is expected. Additional testing is not required. Certification of this design will be submitted as based on past experience. Aluminum diverter strips perform well in-service to protect the underlying parts from damage. The diverter strips perform their intended function well, but can be damaged when struck by lightning. Post lightning strike inspections ensure the diverter strips are intact and functional and are recommended to be included in the service manual.</td></tr>
<tr><td colspan="2">Section 9. Report from Test Engineer Regarding Continued Airworthiness</td></tr>
<tr><td>Test Engineer Name:</td><td>B. Buckingham</td></tr>
<tr><td>Report: (include significant findings and relevance to continued airworthiness)</td><td>Lightning strike diversion effectiveness: With diverter strips installed on the VOR antenna outer radome case, experience has shown that the possibility of damage to the radome cap and the underlying antenna caused by lightning</td></tr>
</table>

	strike can be reduced. Eleven aircraft operators (aircraft type retained) have reported a number (number retained) of instances of VOR antenna damage resulting from lightning strikes. Lightning strikes have caused varying degrees of damage from small pit marks on the antenna elements up to almost complete destruction of antenna elements, coax cables, and fiberglass honeycomb fin tip cap structure. The path of lightning penetration to the antenna is suspected to be the antenna access door metal fasteners as seen from the tests conducted on this design configuration. A sustained lightning strike could cause the VOR system to become inoperative and require repair or replacement of the fin tip assembly before the next flight from service experience. Vertical diverter strips have proven positive experience when bonded on each side of the cap in the region of the VOR antenna on another aircraft type (aircraft type retained). A Service Bulletin (number retained), issued (date retained), concerned reduction in the likelihood of lightning strike damage to the (aircraft type retained) tip cap area. The kit cost listed as (cost retained) and the total labor requirement as (number of hours retained) man hours. A consequence of incorporating the modification would be that the whole fin tip cap would need to be removed to gain access to the VOR/LOC antennas. This is the typical design today for aircraft produced by this manufacturer and is the design used on the aircraft. The modification of the (aircraft type retained) aircraft VOR lightning protection design was optional and the operator had reportedly rejected it because of the low frequency of lightning strike damage to the VOR/LOC antennas and fin tip structure. The operators also considered that, while the additional diverter strips may assist in reducing damage, they would not preclude all damage, particularly from powerful strikes. Operators today experience better performance with VOR antenna installations due to past experience with VOR

	antenna cap designs that include diverter strips installed with compatible materials and appropriate sealants.
Section 10. Design Revision Request	
None. The design is robust against the lightning damage and operational threats.	
Section 11. Revision accepted by Program	
No revision requested.	
Section 12. Description of Final Optimized Design	
Action Taken: None recommended.	
Approval:	
Mr. G Sweers, Lightning Protection Analyst	Original Signed
Mr. Keith Smith, Lightning Protection Designer	Original Signed
Mr. Jacob Owen, Bonding and Earthing Engineer	Original Signed
Mr. John Taylor, Chief Engineer	Original Signed

Figures attached to Assessment Sheet for Empennage VOR Antenna Installation

The following graphics are collected for use in the assessment of the lightning protection reviewed by assessment Sheet ANT001. These graphics were used to identify key component attributes contained within the assessment sheets.

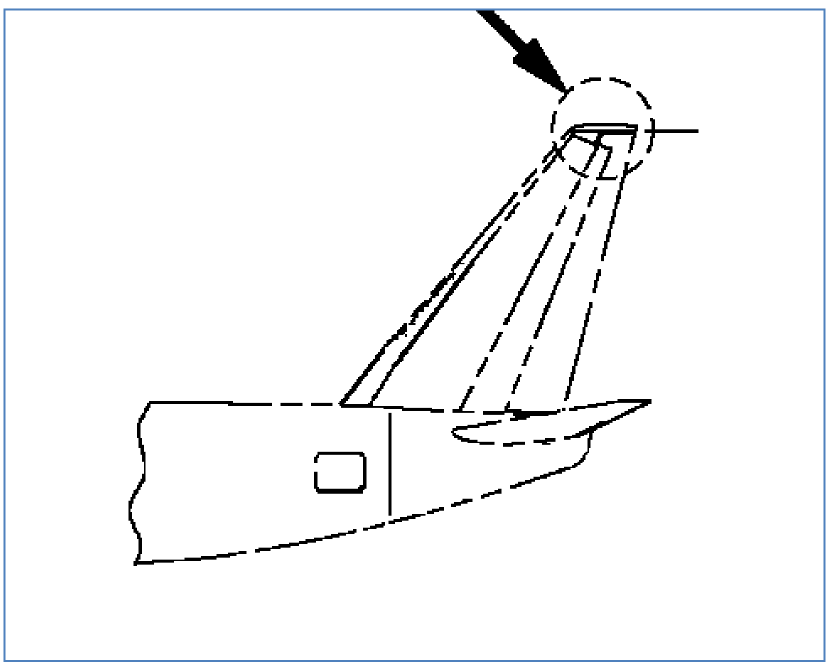


Figure 5-33 VOR antenna installation location

The lightning protection provided for the VOR antenna structural attachment is required to maintain availability of the VOR function through many operating hours in service. In Figure 5-33 the VOR antenna is shown on top of the rudder where lightning strikes can attach directly. The electrical grounding (earthing) of this installation is provided through intimate contact between the rudder fin cap and the surrounding attachment structure. In addition, a strip of metal is provided at the top of the fin cap to also aid in transference of potentially damaging electrical currents associated with lightning strike events.

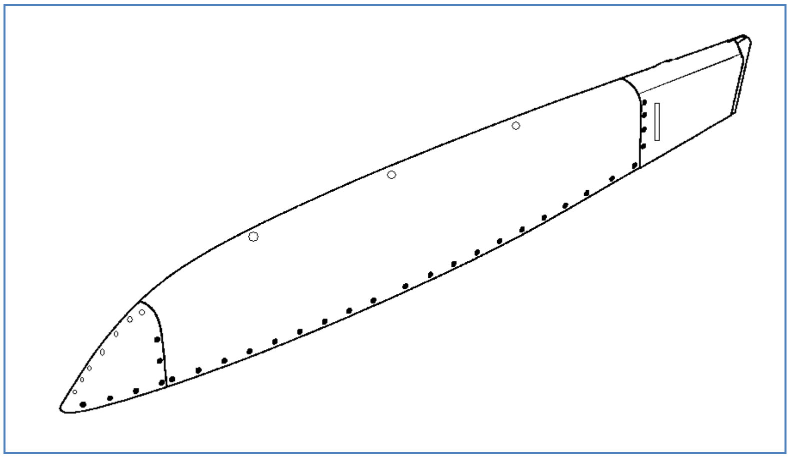


Figure 5-34 Antenna Cap

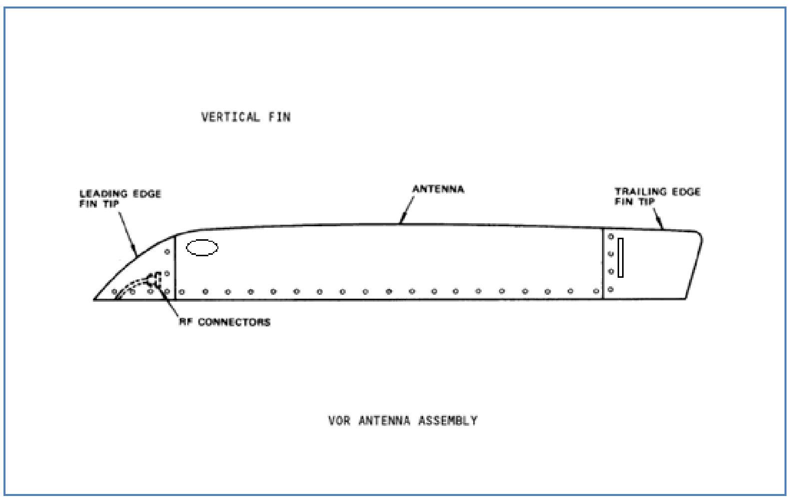


Figure 5-35 VOR antenna cover and lightning strike protection strip

Fasteners are used to secure the fin cap to the rudder structure. The analysis in this case study evaluates the effectiveness of the diverter strip attachments to the rudder fin cap on the top of the fin cap shown in Figure 5-36. Figure 5-37 shows a top 3-D view and the fastener attachments through the fin cap to the rudder tip.

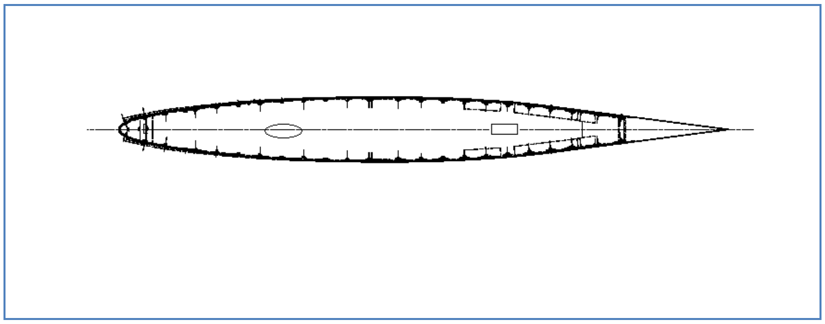


Figure 5-36 VOR antenna cover fastener orientations

Proprietary Graphic Retained

Figure 5-37 VOR antenna cover side view with dimensions

The electrical bond for the fin cap installation is to be measured from the mounting bolt head in Figure 5-38 to the airplane structure. The maximum resistance between the structure and the antenna cover is (resistance value retained) ohms. Certified personnel shall be used to perform the inspection for proper resistance measurement of this installation after completed. Specification (Specification number retained) is used as the appropriate guide for ensuring that the proper installation process is used to achieve the expected resistance.

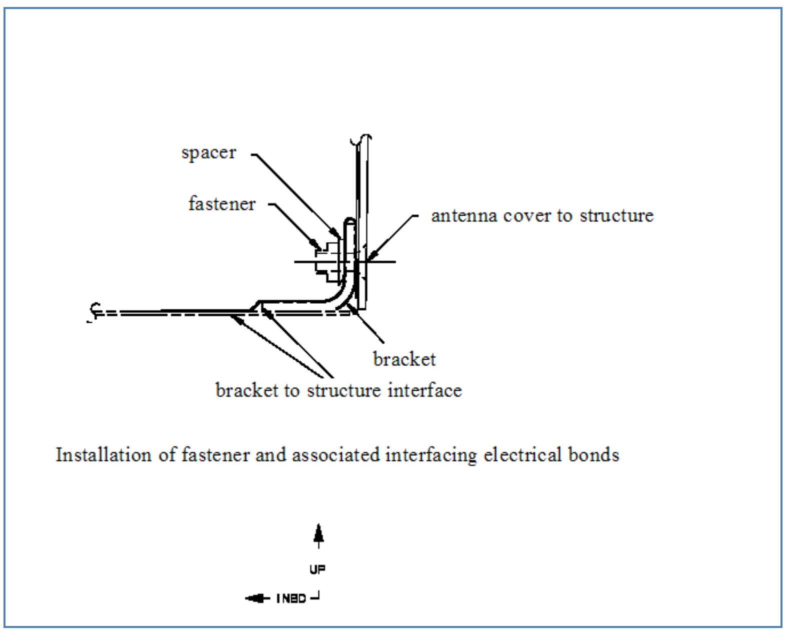


Figure 5-38 VOR fin cap attachment detail

For the fin cap installation attachment to the rudder tip structure, the self-locking fastener is used in Figure 5-38 to secure the installation. The surfaces are cleaned prior to installation and the specification (specification number retained) is used to ensure that the bond surfaces are free from contamination. A corrosion protection is also applied to the surfaces to ensure long term electrical contact. Personnel that are trained in the application of (specification number retained) specification are required to perform the installation.

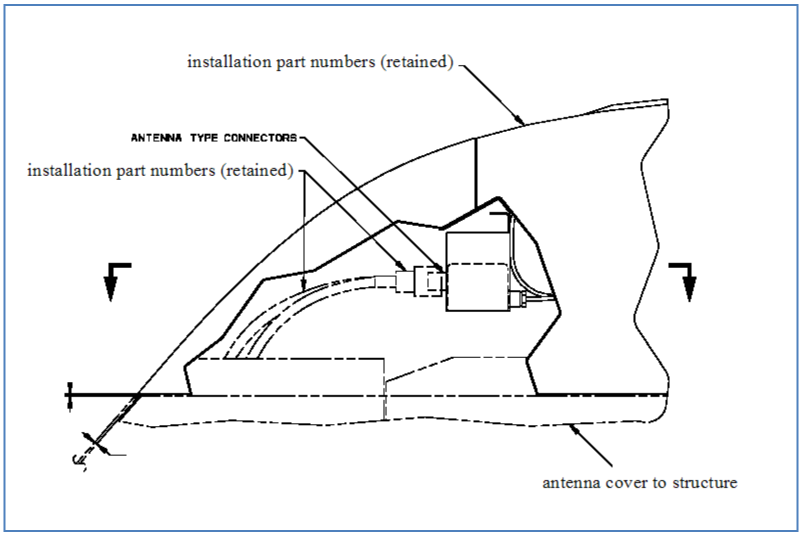


Figure 5-39 VOR fin cap side view cut away revealing VOR antenna connector

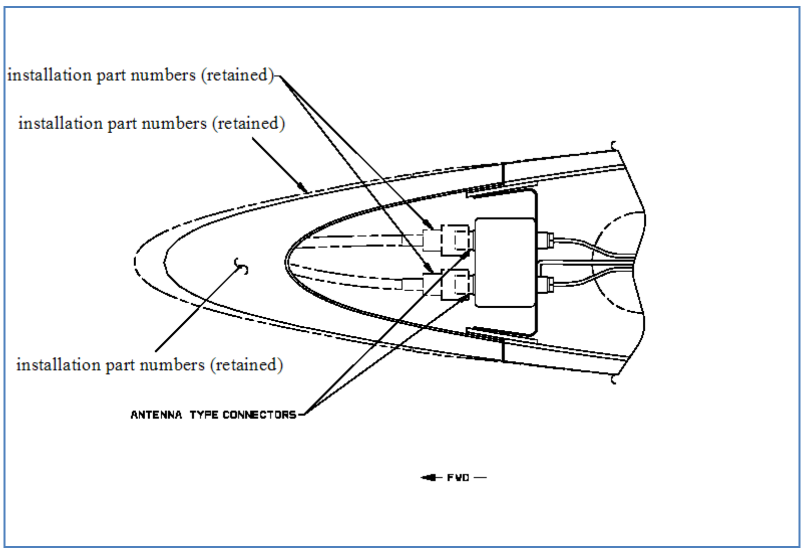


Figure 5-40 VOR fin cap top view cut away revealing VOR antenna connector

Protection of the underlying connector installed on the VOR antenna as shown in Figure 5-39 and Figure 5-40, is provided by applying a good bond between the fin cap and the rudder tip structure while also sealing out the potential for moisture within the antenna assembly. This bond is important to maintain during operation of the aircraft in order to properly transfer lightning energy without the unwanted effects of damage to the antenna cap and potential indirect functional effects to the safe operation of the VOR antenna system.

Part 3: Rudder Structural Protection General Description

Lightning can cause rudder damage. For this reason lightning protection is applied to the aircraft rudder. Lightning strikes damage control surface trailing edges. To understand the process of a lightning strike to an aircraft that results in this damage, one must consider the nature of lightning. Lightning occurs when there is a significant buildup of electricity in a storm cloud relative to some nearby object or region. Thus, if one end of a cloud becomes negatively charged and the other positively charged, lightning will go between the two charged cloud regions to even out the charge; this is called cloud to cloud lightning. As discussed in the lightning phenomenon section of this thesis (reference Chapter Two), lightning will seek a path to ground if the nearest point that will cancel the charge is the earth. This is called cloud to ground lightning. As a lightning strike event begins, lightning energy will follow the path of least resistance. The process of seeking the least resistance to ground will give the lightning to a jagged, forked appearance. As the lightning passes through the air it encounters air of different densities and particulate matter which causes lightning to divert along the path that is best suited for conduction.

Aircraft do not have enough mass to act as an effective final ground for lightning strikes. Strikes that involve aircraft in the ground path pass through the aircraft when the aircraft is the path of least resistance at the time of the event. Thus, lightning must enter the aircraft and then exit it at a different location. Electricity attaches to discontinuities in the aircraft structure. With many discontinuities along the trailing edge, aircraft must design protection against sever damage due to lightning strikes. Lightning seeks the path of least resistance and the greatest discontinuity. Since the trailing edge panels of the aircraft in these case studies are not conductive, the lightning strike current must be diverted to a metallic structure so it may be conducted to another location to exit the plane. There are two ways to direct lightning current away from structure that may cause damage. One is to use flame spray over the surface so that a strike will dissipate across the panel surface to the surrounding structure. The flame spray has a high conductivity so that a hole will not burn through the panel on impact, however, after the initial strike, the bolt will tend to move across the panel to the edge discontinuity where it prefers to be attached. Attachments to trailing edge discontinuities is called “hang on”. Lightning strikes are not instantaneous and they can be followed by repeat strikes following the same path of least resistance. Burning can result along the edge of the panel, as the cross sectional area of the flame spray at the edge of the panel is less than the cross sectional area of the lightning strike. Therefore, some energy may enter into the composite structure and cause a burned damage to the composite structure.

The second method of protection, which is currently being used on the trailing edges of the aircraft rudder assessed in these case studies, eliminates the edge burning problem. It involves attaching a (thickness retained) inch thick aluminum strip to the aft edge of the panel. The fiberglass is such a poor conductor that lightning will only attach at the trailing edge which is protected by the strip. Even if the strike initially attaches to the leading edge of the panel, it will "walk over" the fiberglass on the way to the aft edge.

Case Study 3 Structural Protection – Rudder Protection Case Study and Assessment Sheet

The aircraft manufacturer in these case studies makes use of an anti-static coating called (specification retained) on fiberglass and other plastic surfaces. This coating is intended to facilitate the discharging and positive grounding of static electrical charges to the primary structure. In the case of the rudder, this conductive coating must also be applied to the panel with bonding fasteners for P-static protection. The conductive coating does not have enough conductivity to dissipate a lightning strike. The lightning current will pass through the panel until it finds metallic structure or exits the other side of the panel. As lightning current is known to find the least path of resistance, a lightning strike may go through the panel if an alternative low resistive path is not available.

A design challenge that must be solved pertains to proper transfer of the electricity from the panel to the wing box for conduction to another location for safe discharge. Normally the design path might be from the attach point on the rudder to the horizontal stabilizer where there is the greatest discontinuity of any location on the plane. With the aid of flame spray, the vast majority of electricity passes out of the panel through the bonding fasteners as this is the path of least resistance. Some minor component of the current also passes into the other fasteners that also go through the flame spray. Burn marks around the bonding fasteners as they heat up often results from lightning strike. The presence of burns or melting damage to fasteners is part of the post lightning strike inspection required to be performed by airlines after a lightning strike event. The aluminum strip does not have any designated bonding fasteners; however, the fasteners that are countersunk into the material will have good conductivity due to metal-to-metal contact between the fastener and the aluminum strip. This is the designs path of conduction out of the panel and into the surrounding structure. The number of fasteners available for the conduction, either designated bonding, or countersunk in the aluminum, may need to be greater than that required for P-static dissipation. For the number of bonding fasteners required the manufacturer designers have created appropriate design guides used to establish the rudder aluminum strip installation.

Summary of installation protection requirements for the rudder under evaluation:

a. Protect the surface with (specification retained) conductive coating.
b. Use bonding fasteners. Apply a minimum of (number of fasteners retained) fasteners per panel and no greater than (fastener installation proximity retained) inches between any two on a single panel.
c. Apply a (length retained) inch aluminum strip along aft edge the panel.

Engineering L/HIRF Protective Device Assessment Sheet
Protection Component Name

Rudder Aluminum strip “picture frame” installation on Rudder

Trailing Edge and Earthing Jumper

Section 1. Lightning/HIRF Protection Component Data	
Assessment Sheet Number	STR003 (STR=Structures, FUL=Fuel, SYS=Systems, ANT=Antenna)
Engineer Name:	Byron Billings
Part Number:	Part Number retained
Manufacturer:	Manufacturer name retained
Lightning Protection Zone	Zone 1
Design Service Life Goal:	Design for protection of rudder composite structure. Inspections and repairs may be required after a lightning strike event. No overhaul required.
Date: November 16, 2009	

Section 2. Component Description

System Criticality: Critical

Description:

The rudder protection consists of two aluminum diverter frames, two rudder diverter strips, an aluminum lightning doubler, an aluminum static discharger base, and two (size retained) inch insulated bond jumpers that move +/- (number retained) degrees with the rudder motion.

The diverter picture frames and diverter strips are installed to the outer most layers (OML) of the carbon fiber reinforced plastic (CFRP) rudder panels per (installation specification reference retained) using (adhesive specification retained) as an adhesive bond. The forward edge of the diverter picture frames are connected through the CFRP rudder panels to the aluminum rudder tip closure rib with conductive titanium bolts and collars, per (installation specification reference retained) with (material specification retained). A lightning doubler on the left side and the static discharger base on the right side, bond the diverter picture frames to the diverter strips using conductive titanium screws and blind passivated CRES inserts. The lightning doubler and the static discharger base are installed per (installation specification retained) and sealed with (material specification retained) sealant.

Section 3. Component Purpose and Operational Theory

In general, for composite structure, Zone 1 and Zone 2 areas will require additional conducive material on the outside surface to provide lightning protection. Zone 3 will not require lightning protection except honeycomb structure which uses aluminum core. However, the lightning zones only reflect the probability and severity of a lightning strike. The optimum protection material choice depends on the size, shape, construction, and underlying material of the part, allowable damage as related to safety of flight, environmental durability, and maintenance for the airlines. The materials used for lightning strike protection are either expanded aluminum foil (part specification retained), aluminum picture frame, or diverter strips.

Protection for the rudder is provided by the aluminum strip “picture frame” and the earthing jumper shown in the drawings.

Aluminum picture frames are used for lightning strike protection. Aluminum picture frames are used in areas of flat contours with a high frequency of strikes, and they are also used for economic reasons to allow a part to have multiple lightning strikes without significant damage that would require extensive repair. They are typically implemented on composite primary flight control structure such as rudders, elevators, and ailerons. They are generally placed in the tip areas which are categorized as Zone 1.

A typical frame is made from (material alloy reference retained) aluminum alloy per (specification retained), (thickness retained) inch thick by (width retained) inches wide. The frame is either chromic acid anodized or boric sulfuric acid anodized (preparation reference retained). This process protects the aluminum picture frames from degradation due to corrosion. The frame is then primed with (material and process specification retained).

The aluminum picture frame is subsequently bonded to the final cured part with (sealant specification retained) sealant per (process specification reference retained). Narrow strips of aluminum which may be bonded to the trailing edge of a part are also considered in this category.

The aluminum picture frame must be properly electrically bonded to grounded metallic structure. If attached to CFRP structure as in this application for the (aircraft type reference retained) rudder, a fiberglass isolation ply is required to prevent galvanic corrosion.

Proper bonding and electrical continuity from the aluminum protective strips is essential to continued protection from the direct effects of lightning. Without the aluminum strip protection, potential damage to the rudder could affect the continued safe flight by removing significant amounts of rudder composite material that could cause a negative effect on safe flight.

Section 4. Component Schematic and Installation Details

Installation Details:

The rudder lightning protection is intended to remain installed unless damaged by lightning or other unexpected impact. Repair of the rudder lightning protection is provided in the structural repair manual.

The trailing edge of the left diverter picture frame, left diverter strip, and lightning doubler are joined to the trailing edge of the right diverter picture frame, right diverter strip, and static discharger base through the left and right rudder skin panels using conductive titanium rivets that are wet installed per (installation specification reference retained) with (sealant type reference retained) sealant.

The aluminum rudder tip closure rib is electrically connected to the vertical fin via two insulated bond jumpers (bond jumper part number reference retained).

Bond Jumper description: Terminals are to be completely hot dipped in tin to create (tin thickness reference retained) inches of thickness after punching, trimming, de-burring, and flattening the terminal. Tin material shall be in accordance with ASTM B 339. Tin wicking into the braid is (wicking thickness reference retained) inch maximum to be acceptable. The hot tin dip process including tin composition and flux shall be documented. The bond jumper is a weave of tinned copper braided wires with (number of strands reference retained) strands of number (wire size retained) wire equivalent to (equivalent size reference retained) circular mils.

Two upper aluminum brackets are mounted to the rudder aluminum tip closure rib and two lower aluminum brackets are mounted to the aluminum aft closeout rib of the vertical fin per (installation process specification reference retained) fay surface bond. Each bracket has two conductive titanium fasteners and aluminum alloy collars with a protective conductive coating.

The bond jumpers are composed of tin plated copper terminal lugs with a single hole crimped to insulated tin plated copper stranded wire, with sealant inside crimp barrel and clear sleeve over top of crimp barrel. Two insulated bond jumpers are attached to the brackets per (installation specification reference retained) fay surface bond with (sealant type reference retained) sealant. The insulated bond jumpers are attached with titanium screws coated with protective conductive material, three aluminum washers, and a self-locking cadmium plated CRES nut.

Bond Path Providing Protection:

A. Left and right trailing edge diverters connected through the CFRP skin panels with conductive titanium rivets that are wet installed per (installation specification reference retained) with (sealant type reference retained) sealant.

B. The lightning doubler on the left side and a static discharger base on the right side bond the diverter picture frames to the diverter strips using titanium screws and passivated CRES inserts, per (installation specification reference retained) with (sealant type reference retained) sealant.

C. The forward edge of the diverter picture frames are connected through the CFRP rudder panels to the aluminum rudder tip closure rib with conductive titanium bolts and collars, per (installation specification reference retained) with (sealant type reference retained).

D. Two upper aluminum brackets are mounted to the aluminum rudder tip closure rib per (installation specification reference retained) fay surface bonds, each with two conductive k-coded titanium fasteners and aluminum alloy collars.

E. Two bond jumpers are attached at each end to the upper and lower aluminum brackets per (installation specification reference retained) fay surface bond (sealant type reference retained) with protective coated titanium screws, three aluminum washers, and a self-locking cadmium plated CRES nut.

F. Two lower aluminum brackets are mounted to the aluminum aft closeout rib of the vertical fin per (installation specification reference retained) fay surface bond, each with two titanium aluminum pigmented coated fasteners and aluminum alloy collars.

Mounting hardware is sealed upon installation. Interface between the mounting hardware and the aluminum structure is completed with compatible metals.

Mounting hardware associated with bond path is found to be compatible and properly sealed.

Section 5. Installation Environmental Threats

The diverter strip and bond jumper installation is outside the pressure vessel and exposed to multiple environmental threats.

Description of installed environment:

Installation is outside pressure vessel and exposed to severe temperature changes, contamination, and erosion from particulates, damage from hail or other objects impinging on the rudder of the aircraft during flight.

Flammable Leakage Zone Description and Protection:

Flammable leakage can exist in this location due to potential hydraulic leaks in combination with an ignition source such as lightning or fault currents.

Ratings of environmental threats:

Location: Nose Radome Exterior		
Threat Type	**Rating of threat severity in this location (High, Medium, Low)**	**Installation resistance to degradation (High Medium, Low)**
System Operating Fluids (oil, hydraulic fluid, Grease and Lubricants)	High	High
Chemicals and Applied Fluids (cleaning fluids, fire retardants, de-icing, wing anti-ice fluids, liquid cooling)	High	Medium
Natural Occurring Fluids (condensation, precipitation, humidity, ice, rain, snow)	High	Medium
Temperature Exposure (swings in temperature, and extensive exposure to extreme high or low temperatures)	Medium	High
Vibration (low or high frequency vibration)	Medium	Medium
Fuel (Exposure to fuel)	N/A	High
Flammable Leakage Zone (Yes/No)	Yes	High

Section 6. Assessment of Critical Characteristics in the Installed Environment

The continued airworthiness of associated components within the lightning protection designed bond path is expected to perform the function of minimizing more severe damage to the composite rudder if the aluminum strip were not installed. The rudder aluminum strip has been designed to withstand accidental impact damage. Damage will only occur as a result of accidental physical impact or severe lightning strike that may be evident to the operating crew due to antenna input errors. For lightning strike incidents that do not have an effect on operation of the antenna, service experience shows that installation of the aluminum strips reduces potential for serious damage. Many strikes to this area of the aircraft are noticed by operating crew due to noise while in flight and recorded in the maintenance log book upon arrival to the destination. At that time, the airline operator will conduct an inspection of the rudder and determine repair requirements. Service experience is expected to be similar to other aircraft rudder installation designs. All fasteners are installed with sealant. This reduces ingress of moisture and subsequent degradation of the electrical bond. The interface between mating surface of the antenna and the structure is cleaned and a protective coating of corrosion prevention compound (compound type reference is retained) is applied between the two surfaces. This installation approach will also prevent moisture ingress and potential subsequent corrosion. Fasteners are coated with cadmium, a corrosion inhibiting material, to prevent unexpected corrosion and resulting impedance increases within the lightning electrical bond path. Fastener installations are similar to installations in many other models built by this manufacturer with proven successful performance.

Section 7. Test Plan Input

Testing for the rudder aluminum strip should ensure that all fasteners and interfacing materials are made of compatible material. The rudder aluminum protection strips are included in the rudder design to ensure that lightning strike do not cause significant damage while also providing an electromagnetic window from which the operating antenna below the rudder cap can function adequately. In this design adequate amounts of metallic material are driven by the test results. When the surface ply has the metallic strip attached, the use of appropriate sealants is required. For the metallic surface of the lightning protection strips, a corrosion protection finish is required such as boric sulfuric acid anodized or chromic acid anodized to the surface of the metal. In locations where the metal is expected to provide an electrical bond path, the use of cleaning methods to expose the metal to metal bond shall be used with a subsequent application of sealant to prevent moisture from ingression of moisture into the metal joint over time. For the test of these designs, it is expected that the component be exposed to moisture, salt spray, and temperature fluctuations to simulate as best possible, the effects of the environment over time.

When dissimilar metal such as aluminum are attached or bonded to CFRP, an electric potential difference will exist. Dissimilar metals to CFRP include aluminum, steel (except CRES), cadmium plated steel, cadmium-titanium plated steel, zinc plated steel, and tungsten. In the presence of an ionic solution, e.g. water, the dissimilar metal becomes an anode and the CFRP becomes a cathode. When a galvanic reaction occurs, the dissimilar metal is oxidized and corrodes away. There are a variety of dissimilar metal components which could come in contact with CFRP.

These include:

. (Specification reference retained), Expanded Aluminum Foil

. (Specification reference retained), Aluminum Foil

. Aluminum Picture Frames

. **Aluminum Diverter Strips**

. Fittings

. Fasteners

When aluminum comes in contact with CFRP, a fiberglass ply must be located on the CFRP surface to inhibit galvanic corrosion. The boundaries of the isolation ply must be identified on the drawing picture sheet, if other than a full ply. The knowledgeable engineer will choose the appropriate fiberglass isolation plies for each of the CFRP materials provided in the manufacturers design guide.

In addition to separating dissimilar metals from the CFRP with an isolation ply, galvanic corrosion may occur if the CFRP cut edges are within a (distance reference retained) inch moisture path of the dissimilar metals. To inhibit the galvanic corrosion, the CFRP cut edges must be sealed. The knowledgeable engineer will seal the CFRP cut edges per (specification reference retained).

If fasteners contact CFRP material, the fasteners are typically wet installed (coated in sealant), and the head of the fastener is covered in sealant. The material and process notes for the sealing of fasteners is addressed as an input to this test by the knowledgeable engineer because it is related to mechanical assembly. Mechanical assembly is to be addressed by another knowledgeable engineer where coordination of the mechanical requirements must be integrated with the requirements to protect CFRP from contact with non-compatible metallic fasteners.

Aerodynamic surfaces of composite parts are subject to rain erosion on all surfaces that will be exposed to an angle of attack of (angle reference retained) degrees. These parts, e.g. radome, may require special finishes. If rain erosion is an issue, the knowledgeable engineer will inform the designer to consult the knowledgeable engineer in Materials Technology for appropriate measures to protect the structure.

Section 8. Test Data Results

Tests for this installation have been accomplished by similarity to other past aircraft models. Aluminum “picture frames” and bond jumpers have been installed on other model aircraft (specific aircraft models retained) where the aluminum is mounted to a CFRP structural member and the bond jumper is used to attach the picture frame on a composite structure to primary structure.

Past testing summarizes good results for aluminum strips to possible lightning hazards associated with the operation of the (specific airplane series reference retained) series airplane and makes certain that this airplane and its electronic equipment is adequately protected against lightning discharge. The test results were established by the recent increase in emphasis on system reliability rather than by any special vulnerability connected with the new aircraft configuration. For this reason additional testing was not performed for this specific aircraft type application but rather service experience was used to determine appropriate long term design for the rudder protection. Strike probabilities associated with all aircraft show that the rudder area is struck by lightning without known serious impact to aircraft continued safe flight and landing. Use of this technique has shown in the laboratory that the design will adequately reduce any existing hazard to an acceptable level. The laboratory work was accomplished through the cooperation of principle laboratory technicians with general samples of composite structure and associated adhesion of the aluminum strips to the sample structural member. Lightning threat of 200 amps was applied using the waveforms called out by the industry design standard DO160 document.

Damage to the composite structure was reduced and proven through test when addition of aluminum strips is applied to the structure. The anodized exterior of the aluminum strips reduced corrosion of the aluminum when exposed to (hours retained) hours of salt spray. Damage to the aluminum strips due to lightning were repaired in only a few of the many test cases. Bond jumper testing proved good before exposure to any environmental threats. After exposure to (number of hours retained) hours of salt spray the tin plating on the copper bond jumpers deteriorated slightly. Bending of the webbed jumpers proved to cause fraying and reduced the overall resistance of the bond jumper. The combination of salt spray and flexing of the bond jumpers in test resulted in broken strands and much more damage to the jumper when subjected to the 200 amp lightning strike current. The lightning strike current waveforms were determined by the DO160 document similar to the tests conducted on the entire composite structure composite samples. The bond jumper wire was not connected to the picture frame aluminum strips in a simulated fashion to the proposed installation.	
Section 9. Report from Test Engineer Regarding Continued Airworthiness	
Test Engineer Name:	B. Waltmer
Report: **(include significant findings and relevance to continued airworthiness)**	**Lightning strike diversion effectiveness**: With aluminum strips installed on the rudder trailing edge, experience has shown that the possibility of damage caused by lightning strike is reduced. Use of the tin plated bond jumpers in exposed areas has not proven robust in service and poor performance against corrosion resistance has been repeated in the lab. Some degradation occurred with the bond jumper external Tin coating after exposure to salt spray. Additional degradation occurred after the flex tests. Resistances were measured with a low resistance bond meter before and after the tests were conducted. Resistance of the bond jumper prior to exposure to the environmental threats was (resistance value retained) milliohms. After exposure to salt spray the resistance was (resistance value retained) milliohms, higher than the original measured value. The bond jumper was measured for resistance after the flex tests. This was measured at (value retained) average milliohms above the original degraded value. Bond jumpers that were subjected to the salt spray were not subjected to the flex test. The combination of these two tests is expected to cause more severe degradation than the sum of the two test result averages. The impracticality of testing the bond jumpers under the combined threats resulted in separate

	test results that require a combined effects assessment. Use of cap seals on the bond jumper has shown in test to allow crevice corrosion. Moisture runs down the drip path into the termination point and collects at the terminal fastener location between the terminal and the attached structure. The inability of the fillet seal to keep moisture out of the bond jumper terminal interface contributed to the degradation. In disassembly of the terminal joint, it was found that voids caused areas within the sealant application to capture moisture. Wet operating environments or corrosive fluids contribute to the problem. In addition, stress corrosion was noted due to the combined stress associated with the flexing of the terminal, cracking of the sealant, and tensile stresses created in the corrosive environment.

Section 10. Design Revision Request

Based on results in service and duplication of the problem in the laboratory testing, it is recommended that the installation designer consider two potential alternatives to applications for bond jumpers in corrosive environments.

1. Use of fay surface bonding.

Design revision request suggests that the laboratory include a fay surface bond in place of the fillet seal bond for applications of these bond jumpers in corrosion environments. Fay seal bonds are more effective in eliminating moisture within fay surfaces between the fastener, washer, terminal and mounting structure. For these fay surface bonds, suggest the use of process specification (process specification reference retained). This application will ensure use of sealant between all faying surfaces in the fastened terminal and a torque of the fastener sufficient to provide the conductive surface contact while squeezing out the excess sealant and creating a more moisture tight bond protection.

2. Use of compatible fasteners, washers and terminals.

In selecting the fasteners, washers and terminals, ensure that the materials interface is as compatible as possible to reduce galvanic corrosion activity. Use of a tin plated jumper should also be evaluated to ensure that the mounting surface of the aircraft structure is of the most compatible material. This can be achieved by reviewing the galvanic materials chart and selecting material exterior finishes that are closest together within the chart. As base materials may vary, it is most important to ensure that the finish on the exterior of the fastening systems and mounting structure are both conductive in nature and represent a low probability of corrosion.

3. Improved design alternative - Use of Nickel plated bonding jumper.

Nickel plated copper bond jumpers offer improved protection from moisture and degradation due to environment. The bond jumpers are composed of nickel plated copper terminal single hole lugs

crimped to insulated nickel plated copper stranded wire, with sealant inside crimp barrel and clear sleeve over top of crimp barrel. This design is more effective in eliminating moisture ingress into the bond jumper wire. The tin plated bond jumpers tested in the lab do not offer the same protection from moisture and should be used at locations on the aircraft that have a less moisture prone environment. The nickel plated bond jumpers are also insulated along the entire bond jumper wire as compared to no insulation on the tin plated bond jumper. In order to attach these nickel plated bond jumpers to aluminum structure effectively, the insulated bond jumpers may be attached to the aluminum brackets per (installation process specification reference retained) fay surface bond with (Sealant type specification reference retained) sealant. The insulated bond jumpers should use corrosion resistant outer coating on the fastener titanium screws, aluminum washers, and a self-locking cadmium plated CRES nut for the best overall performance.
Section 11. Revision accepted by Program
The program has evaluated the results of the test, in service evidence of performance in this moisture-prone location, and has determined that the recommended change to a nickel plated and insulated copper bond jumper is acceptable for this installation application.
Section 12. Description of Final Optimized Design
Action Taken: Revise the drawings and design to replace the tin plated copper bond jumper with the insulated nickel plated copper bond jumpers attached to the aluminum bracket structure with the recommended hardware and sealant process referenced in this evaluation.

Approval:	
Mr. G Sweers, Lightning Protection Analyst	Original Signed
Mr. Keith Smith, Lightning Protection Designer	Original Singed
Mr. Jacob Owen, Bonding and Earthing Engineer	Original Signed
Mr. John Taylor, Chief Engineer	Original Signed

Figures attached to Assessment Sheet for Rudder VOR

The following graphics are collected for use in the assessment of the lightning protection. These graphics were used to identify key component attributes contained within the assessment sheets.

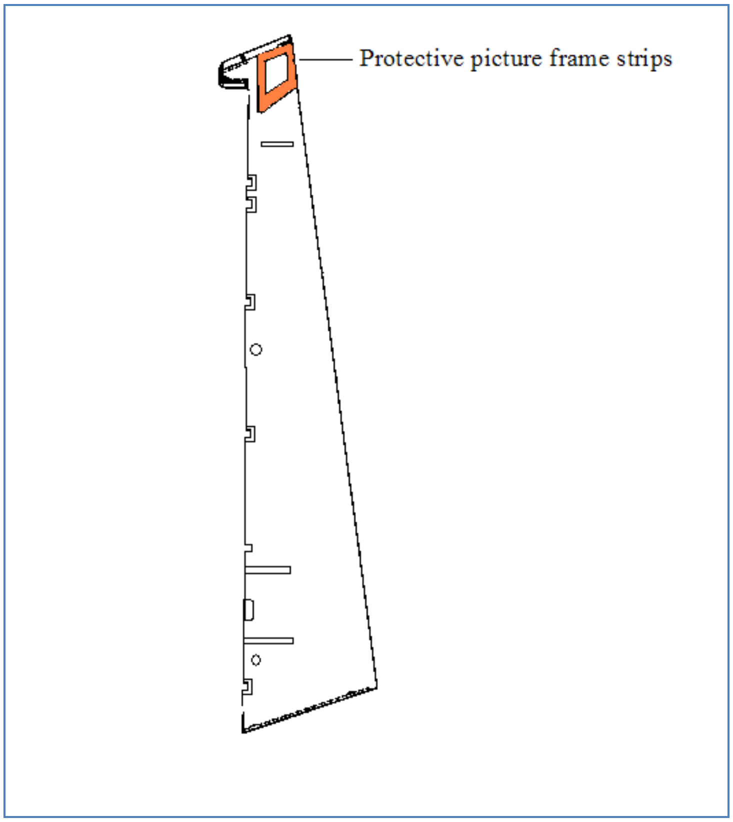


Figure 5-41 Rudder lightning protection installation locations

Proprietary Graphic Retained

Figure 5-42 Rudder lightning strike locations service history

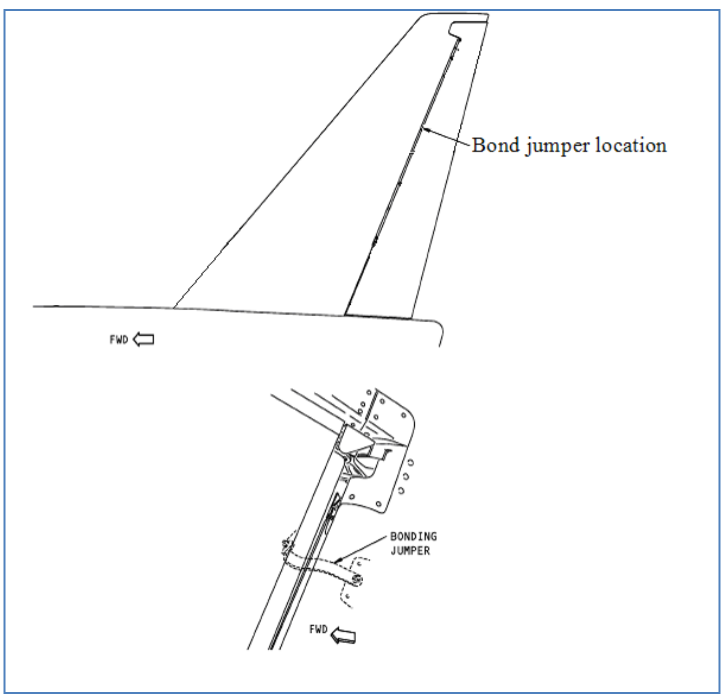


Figure 5-43 Rudder bond jumper installation

The bond jumper (strap) used in protection of the rudder is made of a braided copper construction with a tin outer finish. The bond jumper shown in Figure 5-44 is flat braided and can be used in locations where the bond jumper terminal orientation does not exceed a twist in the jumper beyond (twist limit retained) degrees between terminals. The manufacturer designated part number is (part number retained) and is tin plated copper with a hot tin dipped thickness of (thickness specification retained) inches thick.

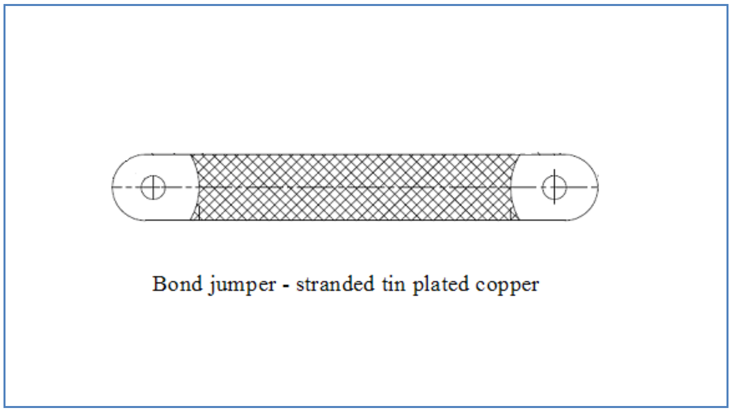


Figure 5-44 Aircraft rudder bond jumper design detail (dimensions retained)

5.7.5 Aircraft Systems Direct Effects Protection against Fuel Ignition

Lightning protection to reduce fuel ignition sources caused by lightning for these case studies consists of the following:

1. Fuel Tank Skins Components
    a. Minimum thickness of (thickness value retained) inches of aluminum alloy
    b. Skin joint (including to spars) sparking eliminated through use of inherent metal to metal bonding, fastening and sealing techniques (uses aircraft (aircraft type retained) wing skin joint test samples proving no sparks)
2. Fuels Tank Access Doors Components
    a. Traditional satellite clamp ring to fasten door to wing skin
    b. Knitted metallic mesh mounted between access door and skin
    c. Non-conductive (material retained) dielectric strip between outermost periphery of the door and the wing skin internal to tank to eliminate possibility of sparking in wing tank
    d. Door materials use either a high impact door design with (material retained) honeycomb door and (thickness of metal retained) aluminum face material on the exterior side of the door with a nylon sheet on the inside of the door or a cast aluminum and a minimum thickness of (thickness retained) inches to protect against energy penetration.
3. Surge Tank Fuel Vent Outlet Door Assembly Components
    a. Bolt assembly used to attach door to the wing skin is designed to transfer lightning currents. Fuel sealant is used to eliminate potential sparking during a lightning event.

b. Rubber gasket between door and wing skin is bonded to skin through multiple fasteners. The rubber gasket provides a dielectric barrier between the door and the wing structure to prevent plasma blowout "sparking".
c. The vent is shaped with curved edges to avoid sharp edges in the opening design where "streamering" can occur causing an unwanted ignition source.
d. Above the scoop is an aluminum lower duct that is fay surface bonded to the vent door to prevent spark and provide a designed current path.
e. A flame arrestor and aluminum vent standpipe are also installed above the fuel vent outlet. The flame arrestor and standpipe are bonded to the lower duct via a fay surface bond providing a designed resistance selected by the designer between the standpipe and lower duct, the lower duct and the door, and the flame arrestor and the lower duct.

4. Surge Tank Pressure Relief Valve Components
    a. The Surge Tank Pressure Relief Valve - is used when the vent outlet is blocked. It is made of a flush mounted poppet value constructed of cast aluminum that is flush with the vent outlet cast aluminum door when closed.
    b. Fay surface bond - The surge tank pressure relief valve is electrically bonded to the door that provides a specified resistance value. The housing encasing the valve is fay surface bonded to the door to provide the current path for lightning during a strike event.
5. Fuel Tank Measuring Sticks Components
    a. Measuring stick assembly is installed on the lower wing skin panel and fuel tank access doors. There are several measuring sticks mounted in the main and center fuel tanks. The assembly includes a base plate, only for the access door installation and a gauge assembly.
    b. The gauge assembly is made up of a non-conductive thermoplastic poppet and retainer that is attached to a metallic base.
    c. In one design, the fuel access door is made of a nylon honeycomb substrate to sustain potential impact with (measure retained) inches of aluminum on the outside.
    d. In another design, the fuel access door is made of cast aluminum and is (measure retained) inches thick.
    e. The third type of measuring stick is mounted with a metallic base flush to the lower wing skin. The base plate is mounted to the cast aluminum doors and wing mounting is similar to that successfully used on the (aircraft types retained). The base plate of the stick is mounted to both types of access doors with four CRES lock bolts with alodined washers and CRES collars. This buildup achieves a low resistance electrical path from the mounting plate to the door. The base plate lock bolts and internally exposed joints between the base plate and the door are covered with tank sealant.
6. Fuel Tank Sump Drains Components – used to remove accumulated water from the fuel tanks.
    a. Sump drains are in a housing that is fay surface bonded to the wing skin.
    b. Main tank installations are located in lightning Zone 2A and are considered lightning proof.
    c. Center tank sump drain valves are located in lightning Zone 2A and have a valve cover that is are bonded to structure via a bonding jumper and meets

the minimum thickness requirement of (thickness value retained) inches to prevent lightning energy penetration into the tank.

d. Surge tank sump drains are located in lightning Zone 3 and are not lightning proof. Installation is standard type 1 bolt-on drains.

7. Fuel Quantity Indication Components
   a. Fuel Tank Compensators - are AC capacitive probes that measure the volume of fuel and density of fuel. The tank unit consists of two concentric metal tubes. The inner tube has a varying diameter so that the capacitance of the tank unit is proportional to the volume of fuel in which it is submerged. The upper and lower ends of the outside of the unit, including the ends of the outer tube, are covered by a non-conducting cover to ensure that inadvertent contact between the electrical portions of the unit and any grounded structure will not short out the unit. The minimum gap between the inner and outer tube is (gap measure retained) inches. The compensator, a capacitor device like the tank unit, is located at low point in the tank where it is normally totally submerged so that its measured capacitance varies only with fuel dielectric. Minimum plate spacing for the compensator is (measure retained) inches. Each probe is supported at two points, one near each end of the unit. The support structure uses a hinged clamp which closes around the tank unit and is locked closed by a quarter turn fastener. Electrical connections use different size self-locking threaded inserts for impedance shield with the wiring exiting the terminal downward and retained by a wire retention clamping feature on the terminal block. The design ensures that terminals cannot be rotated sufficiently to contact each other or any electrically conductive surface. All wire terminations are crimped and soldered or crimped. Shielding within the terminal block is provided to minimize the amount of stray capacitance between the wires. A (voltage level retained) VAC dielectric test is conducted on all probes to determine if the construction is adequate to prevent sparking internally to the probe. This test ensures that the probe wiring is isolated from the probe chassis.
   b. Densitometer – Inherently shielded from lightning attachment by the location within the fuel tank. The optional densitometer used in the other aircraft (aircraft retained) fuel quantity indicating systems incorporates a vibrating cylinder. The cylinder is an integral part of the hermetically sealed sensor unit. The sensor unit is mounted inside the housing of the densitometer. Fuel flows into the densitometer housing through port holes on the side walls of the housing where it comes in contact with the inside wall of the vibrating cylinder. The frequency of vibration of the cylinder varies with density. This frequency is measured and the density of fuel is then calculated using a frequency-to-density relationship. The densitometer housing is fay surface bonded through a foot on the unit to a mounting bracket that is either driven rivet bonded to the rib or a jumper is used and attached to a bonding clip that is driven rivet bonded to the rib. Also, the sensor unit is electrically bonded to the densitometer housing. The electrical coil internal to the sensor units, used to induce and measure the frequency of vibration, are electrically isolated from the sensor unit housing. A (voltage retained) VAC dielectric test is conducted on each unit to ensure this electrical isolation is maintained

during construction of the sensor unit. The sensor unit is identical to the unit that is used on other (aircraft references retained) airplanes.

c. Spar Penetration Protection - Wiring to the tank units, compensator and densitometer inside the fuel tanks are routed through a spar connector which penetrates the fuel tank. The electrical connector flange, inside the fuel tank, is fay surface bonded to structure to deplete any electrostatic charge generated due to fuel movement. Shielding is provided for the wiring outside the fuel tank. The shield is grounded to structure both at the processor and at the forward or aft spar and any intermediate connections.

8. Overboard Drain Mast Components
   a. Drain Mast - The (airplane references retained) airplane fuel system drains any leaked fuel from the shroud surrounding the Auxiliary Power Unit (APU) fuel feed line via a drain mast. The mast also drains hydraulic fluid through a separate tube. The mast protrudes down approximately (value retained) inches from the fuselage just aft of the wheel well on the left hand side. It is made of a foam filled fiberglass shell, adhesively bonded to an aluminum mounting flange. The fuel line that is foamed into the mast is electrically bonded to structure via a bonding jumper. The metal fuel line in the mast is electrically isolated from the metal tubing in the shroud drain line by a hose with a very high electrical resistance. A flammable air/fuel mixture may exist inside, around and/or outside the shroud.
   b. Flame Arrestor - In the event that an ignition source exists in this area, a flame arrestor has been installed inline within the fuel tube to prevent the flame from propagating into the fuel shroud area of the airplane. The flame arrestor is made by (manufacturer retained) and is installed approximately (distance retained) inches from the exit. The arrestor is a conventional design identical to that used on previous aircraft (manufacturer retained) models.
9. Fuel Feed and Refuel/Defuel System Components - The fuel feed and refuel/defuel systems provide for engine and APU fuel feed, tank refueling, defueling and fuel transfer between tanks on the ground. The system consists of aluminum tubing, tube fittings, pumps, valves and sensors that are mounted inside and outside the tanks and on the front and rear spars. All wiring to the fuel feed, refuel and defuel components are routed external to the fuel tanks, except the wiring to the fueling valves which are routed through an aluminum conduit to a float switch installed inside the associated tank. The external wiring is shielded from the component to the fuselage. The purpose of the shielding is to prevent excessive induced lightning voltages from entering into the fuselage. The following lists the details of the lightning and electrostatic discharge protection provided for each component.
   a. Engine Fuel Feed - The engine fuel feed supply line runs from the fuel distribution ring inside the engine, to a boost pump mounted on the engine, up and aft along the strut and then penetrates into the fuel tank at the front spar. The tubing from the fuel tank front spar to the engine driven pump is segmented with each section tied together with (ampere rating retained) amp bonding jumpers for fuel static relaxation. The fuel feed tube coupler (bulkhead fitting) at the front spar of the fuel tank is fay surface bonded to the front spar for lightning currents dissipation and static charge dissipation.

b. Fuel Tank Boost, Override and DC Pumps - The boost, override and the optional DC pumps are used to move fuel from the fuel tanks to the engines. A total of (number of pumps retained) boost pumps per main tank, (number of pumps retained) override pumps for the center tank and one optional DC pump for the left main tank are provided. These pumps are identical to those utilized on the (aircraft type reference retained) airplanes. The main tank boost pumps are the same as the (aircraft type reference retained) main tank boost pumps. The pump housings are mounted on the rear spar with the exception of the forward main tank boost pumps, which are mounted on the front spar. The pump housings are fay surface bonded inside the tank from the housing to the spar. In addition, two (ampere ratings retained) amp bonding jumpers are installed from the casing of the pump motor to structure for power fault current. The maximum resistance between pump motor casings to structure is (resistance rating reference retained) ohm. Since the pump housing and the motor casing are bonded to structure, induced transient on the components' wiring will not create an ignition source inside the fuel tank. Exposed joints between the pump housing, the wing skin and the bolts are covered with tank sealant.
c. Fuel Pump Pressure Switches - A pressure switch is connected to the outlet line of each fuel pump. Each switch is mounted on the front/rear spar so that the electrical connector is outside the fuel tank. The fuel pump pressure switches are mounted on the front and rear spars to a bulkhead fitting. The bulkhead fitting is fay surface sealed from the inside of the fuel tank. The joints between the bulkhead fitting and the inside/outside of the wing skin are covered with sealant.
d. Fuel Shutoff Float Switch - The volumetric shutoff sensor is a magnetic float switch that is mounted inside the fuel tank to limit the tank capacity. The switch is normally closed when the tank is less than full. The power to the fueling valve (voltage reference retained) is routed through this switch via wiring enclosed in an aluminum conduit. The conduits for the main tanks are filled with grease in order to prevent water accumulation and freezing. The center tank conduit opening is on the right hand wing and does not contain any grease due to its adequate drainage capability. The conduits are supported by brackets within the tank and a fitting on the front spar. The wires are insulated and protected by a grommet at the conduit entry. The wires external to the conduit on the leading edge of the front spar are shielded and grounded to structure prior to entry into the conduit.
e. Fueling Valves - The fueling valves are fuel pressure actuated, commanded by an electrical solenoid driven pilot valve. The solenoid is located external to the fuel tank and is enclosed in an explosion proof chamber. The chassis of the solenoid is electrically bonded to the valve body. The valve body is mounted to a gallery type fueling manifold which is faying surface bonded to the front spar with a maximum resistance of (resistance value retained) ohms. The solenoid/valve/body installation is identical to the installation used on the past similar airplanes (specific reference to aircraft retained).
f. Fueling Receptacle - The fueling receptacle provides the necessary hardware for connecting the ground pressure fueling equipment to the airplane

refuel/defuel system. There are no electrical connections to the receptacle. The receptacle is an integral part of the fueling manifold installed on the front spar of the right hand wing, which is fay surface bonded to the front spar. In addition, the receptacle is bonded to structure via a bonding jumper with a maximum resistance of (resistance value retained) ohms.

g. Manually Operated Defuel Valve - The defuel valve body is identical to the engine fuel shutoff valves and the fuel cross feed valve. The valve is attached to the defuel valve adapter assembly which is mounted to the front spar. The adapter plate is faying surface bonded to the front spar with a maximum resistance of (resistance value retained) ohms. The adapter plate is fillet seal from the outside and the fasteners which mount the adapter plate to the spar are covered by tank sealant. The defuel valve handle is attached to the adapter plate using four screws.
h. Motor Operated Valves - Cockpit switches control the motor operated valves in order to control fuel routing throughout the fuel system. All employ a mechanical valve inside the fuel tank with a shaft drive penetrating the spars. The valve motor is external to the fuel tanks and is encased in an explosion proof chassis. The main engine shutoff valves are mounted on the front spar whereas the APU fuel shutoff valve and the fuel cross feed valve are mounted on the rear spar. This design and installation has been successfully used on several other model aircraft designed in the past (specific reference to aircraft retained). A fay surface bond is achieved outside the tank between the spar, the adapter plate, and the motor driven actuator.
i. Fuel Water Scavenge Jet Pumps - A system of jet pumps (one in each main tank and two in the center tank) supplied with motive flow from the main tank AFT boost pumps and the center tank override pumps are provided to continuously remove water from the fuel tank sumps. A fuel scavenge jet pump is also installed (driven by motive flow supplied from the main tank FWD boost pump) to reduce the center tank unusable fuel quantity. There are no electrical wiring associated with these pumps. The pumps are spar mounted via a spar fitting which is fay surface bonded to the spar.
j. Fuel Temperature Sensor - The fuel temperature sensor is mounted through the rear spar into the main tank. Wiring to the sensor is routed along the rear spar external to the tank. The resistance sensing element is completely sealed from the tank exterior by an aluminum case. A fay surface bond bonds the sensor to the rear spar.
k. Hydraulic Line Penetrations to Fuel Tanks - Hydraulic lines are routed into the main tanks for connection into hydraulic fluid heat exchangers. Protection from sparking inside the fuel tanks is achieved by fay surface bonding all hydraulic lines penetrating into the fuel tanks. The bond is made on the outside of the wing rear spar with the surface alodined to provide the required electrical conductivity. The maximum allowable resistance between structure and the bulkhead fitting at the fuel tank penetration interface is (resistance value retained) milliohm. In addition, each penetration, inside the tank has peripheral fillet tank sealant which will prevent sparking inside the tank in the unlikely event of arcing at the interface. The maximum allowable resistance between different tube sizes and the bulkhead fitting are called

out in the manufacturers bonding design specification. Hydraulic lines within the fuel tanks are made of aluminum or titanium and incorporate perma-swage fittings at production breaks. The permanent swage fitting is a close tolerance metal to metal interface used for high pressure application. The fittings were subjected to a (ampere value retained) amp component B surge current to determine if sparking occurred outside on the fitting. From the test results, a permanent swaged coupler fitted on either alodine aluminum or titanium tubes prevents any sparking between the interfaces. The (ampere value retained) amp test level is twice that required by MIL-STD-1757. A current distribution analysis was done to determine the maximum current that will be conducted on the hydraulic lines inside the tank in the event of a direct attachment to the tubes outside the tank. The current levels calculated are well below the test level. The maximum allowable electrical resistance for tube to tube connections inside the fuel tank are called out in manufacturer specification (reference retained).

5.8 Aircraft Lightning Strike Case Study for Indirect Effects

The indirect effects of lightning arise as transients seen within the airframe and on the wire looms that interconnect the various sub-systems.

Lightning traveling on the exterior skin of an aircraft has the potential to induce transients into wires or equipment beneath the skin as shown in Figure 5-45. These transients create lightning “indirect” effects. Careful shielding, grounding (or earthing) and the application of surge suppression devices avert problems caused by indirect effects in cables and equipment when necessary. Every circuit and piece of equipment that is critical or essential to the continued safe flight and landing of an aircraft must be verified by the manufacturers to be protected against the adverse effects of lightning in accordance with regulations set by the Federal Aviation Administration (FAA) or a similar authority in the country of the aircraft's origin.

Figure 5-45 Typical lightning strike indirect effects current path

Transients created by lightning strikes are addressed by tests and design criteria in Section 22 of RTCA DO160E [5.3] and are specific as to type, duration and level of test. Each unit or component of a system can be tested for damage by direct injection of the transient onto its interconnecting pins; testing is also performed on systems by injection of the indirect lightning transient onto interconnecting cable looms. The design of the aircraft in these case studies includes protection against internal zone threats and appropriate protection based on the electromagnetic threat model. Considerable progress has been made in creating modeling tools over the past 15 years which has resulted in many different manufacturer solutions to establishing electromagnetic protection designs in practice.

The interaction of lightning with the aircraft in these case studies induces voltages and currents in the onboard wire harnesses, which can cause critical electronic equipment damage or malfunction, thus compromising the flight safety. If electronic equipment needs to be operated in a region subject to changing electromagnetic fields, and if the currents generated by these fields are considered harmful, the recommended approach to mitigating the harmful effects is to shield and ground the electronic equipment and the interconnecting wiring. As a result, electrical currents generated by lightning or HIRF then circulate through the equipment enclosure to ground without affecting internal circuitry. This enclosure practice extends to interconnecting wiring through the use of cable shielding; that is, the shield is the enclosure that is grounded. Other damage mitigation considerations include the location of the equipment and wiring, use of effective wiring, use of good grounding practices, and building equipment to withstand transients. These tactics are incorporated into the design of the airplane within the case studies.

The lightning interaction with an aircraft is modeled using industry developed computational tools developed for the complete analysis of the electromagnetic fields inside and outside the aircraft struck by lightning, and for the evaluation of the indirect lightning effects induced in the aircraft wiring system. The estimation of voltage magnitude and currents induced on shielded and unshielded wiring and the utilization of shields to reduce the level of these effects in sensitive circuit's results in shielding and grounding solutions that require an airworthiness analysis such as the one developed within the methodology contained in this work. The reduction of magnetically induced voltages can be accomplished through Line Replaceable Unit Internal Protection or by using shielded cable protection or a combination of both. Circuit design within avionics units are part of the design solution used to minimize induced effects however, these protection components such as suppression devices located within the electrical and electronic equipment are excluded from these case studies to simplify the data presentation.

For shielded cable protection, several methods are available which reduce the magnetic coupling of voltages in cables. It is possible to design circuit configurations in which equal and opposite self-canceling voltages are induced in the wiring circuit. Typically, this is accomplished using twisted pairs of wires to reduce coupling. At frequencies at or below 5 kHz, a twisted pair can provide over 20 DB of magnetic coupling reduction. At the 5 kHz frequency however, copper braid shielding will provide practically no electromagnetic coupling protection. As the frequency of the threat is increased above 5 kHz, the effectiveness of the copper braiding for protection against magnetic coupling will improve.

For an optimum effective decoupling solution throughout the lightning frequency spectrum, twisted pair conductors enclosed by a conventional copper braid shield are employed in this design commonly called “twisted, shielded pairs”. The effectiveness of twisted pair wires depends on the uniformity of the twisted wires and tightness of the twist employed. A shielded twisted pair with the shield terminated on one end is normally used to protect against low frequency interference. However, open shields are susceptible to arcing from the high currents associated with lightning. In this case, a twisted pair with the shield grounded at each end is the preferred wiring for reduction of magnetic and electrostatic coupling. The optimum circuit design for reducing magnetic coupling for a single conductor shielded wire is that in which the signal return is through the shield as in coax cables and the shield is grounded to the ground plane at one point. The principle involves having the shield loop area less than or equal to the circuit loop area, with the loop formed by an active circuit and its source return path, in order to minimize shield flux linkages. This circuit offers somewhat better protection than does the unshielded twisted pair of 20 twist/m grounded at one point. The approach is valid only when considering double ended or ungrounded circuits. If single ended or grounded circuits are being used, the shield would be effectively grounded at each end and a complete loop would exist.

Bonding of grounds associated with indirect lightning protection can be created by use of existing structural bonds or addition of bond jumpers within the design. Low impedance structural bonds are a critical component of lightning protection schemes. A closed loop shield with perfect conduction completely isolates the volume enclosed from external magnetic sources such as lightning. The closer that a shield can come to a perfect enclosure, the lower that the leakage of electromagnetic energy from an external source will be experienced on aircraft systems. Since environmental degradation is common when an aircraft is exposed to environmental threats during operation, effort is required to ensure the long term effectiveness of the shields and bonds.

For lightning indirect effects, an aircraft development program is required to comply with Federal Aviation Administration Regulation FAR 25.1316, “Systems Lightning Protection” [5.54].

The intent of the protection provided to comply with this regulation is as follows:

(a) For functions whose failure would contribute to or cause a condition that would prevent the continued safe flight and landing of the airplane, each electrical and electronic system that performs these functions must be designed and installed to ensure that the operation and operational capabilities of the systems to perform these functions are not adversely affected when the airplane is exposed to lightning.

(b) For functions whose failure would contribute to or cause a condition that would reduce the capability of the airplane or the ability of the flight crew to cope with adverse operating conditions, each electrical and electronic system that performs these functions must be designed and installed to ensure that these functions can be recovered in a timely manner after the airplane is exposed to lightning.

(c) Compliance with the lightning protection criteria prescribed in paragraphs (a) and (b) of this section must be shown for exposure to a severe lightning environment. The applicant must design for and verify that aircraft electrical/electronic systems are protected against the effects of lightning by:

(1) Determining the lightning strike zones for the airplane;
(2) Establishing the external lightning environment for the zones;
(3) Establishing the internal environment;
(4) Identifying all the electrical and electronic systems that are subject to the requirements of this section, and their locations on or within the airplane;
(5) Establishing the susceptibility of the systems to the internal and external lightning environment;
(6) Designing protection
(7) Verifying that the protection is adequate.

Induced Currents travel along aircraft system transport components and looms. When lightning strikes an aircraft it travels along a path with a current magnitude varying with time [5.11]. The transient nature of the lightning strike's current also creates a transient magnetic field which can induce currents into nearby circuits created by grounded conductive components. Faraday's Law of Induction states "The Electromotive Force (EMF) induced in a circuit is directly proportional to the time rate of change of the magnetic flux through the circuit". The induced electromotive force or EMF in any closed circuit is equal to the time rate of change of the magnetic flux through the circuit [5.13].

Faraday's law of electromagnetic induction states that:

$$\mathcal{E} = -\frac{d\Phi_B}{dt},$$

Figure 5-46 Faradays Law

Thus:

$\mathcal{E}$ is the electromotive force (emf) in **Volts**
Φ_B is the magnetic flux in **Webers**

In physics, electromotive force, or most commonly emf (seldom capitalized), is the external work expended per unit of charge to produce an electric potential difference across two open-circuited terminals [5.12]. The size of the surface in which the flux passes through in the circuit controls the amount of EMF induced along with the magnitude and transient behavior of the magnetic flux. The presence induced EMF combined with the resistance of the circuit creates a current within the circuit.

5.8.1 Aircraft Design Example of Induced Current Threat and Case Study

The following demonstrates the effects of lightning current on an installed system infrastructure. In this example, a tube is ground in two locations on a spar and runs parallel to length of the wing. During a wing tip lightning strike in which the current travels tip-to-tip, the EMF induced onto the tubing is proportional to the length of the tubing run parallel to the path of the lightning strike. Currents running through tubing in an aircraft design must be modeled so that the appropriate earthing can be applied to the design. Current flow such as that shown in Figure 5-47 will rely on good conductive joints in the entire path and also appropriate sealants where there may be the potential for sparks to be created at conductive interfaces where there is a potential for air gaps.

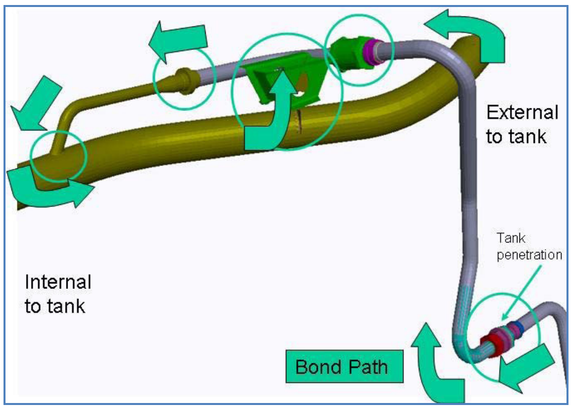


Figure 5-47 Typical bond path for current flow on transport elements at lightning strike

Parallelism

Parallelism is important due to the formation of the magnetic fields. Magnetic fields form along a path which obeys the right hand rule. Given a current traveling in the vertical direction the magnetic field lines will look like concentric circles centered on the path of the current. In an aircraft, tubing that runs parallel to the lightning current in a tip-to-tip conductive path will expose a circuit in which the magnetic field will pass through, while perpendicular tubing runs will not. Another way to view this is to imagine the resulting current. The resulting current induced from a magnetic field always travels in a path normal to the magnetic field which caused it (right hand rule). In parallel runs, the current can flow in a direction that will create its own magnetic fields in the same plane as the ones that created it. In perpendicular tubing runs the current will be flowing in a path that is in the same plane as the original magnetic field, thus creating a field which is normal to the field which created it and will not oppose the original field.

Diffused

Diffused is the term used by some aircraft manufacturers to describe induced currents which occur within the Fuel Tank.

Faraday Cages

It was once assumed that aircraft fuel tanks perform similar to a Faraday Cage, eliminating the induction of EMF onto in-tank components. The [15] FAA Special FAR

(SFAR) 88 investigations have shown that although the tanks do act as a shield, they are not absolute, and the EMF that can be present during a lightning strike needs to be considered in the ignition prevention design of a fuel system. This may because Faraday Cages shield against rapidly changing electromagnetic and electrostatic fields, but do not shield against static or slowly changing electromagnetic fields.

Conducted Current

After lightning strikes the aircraft, it conducts along the structure of the aircraft until its exit point. In aluminum aircraft, with a lightning strike on the wings, it is assumed that the current stays on the exterior structure and does not energize internal structure. The electrical current generally stays on the upper and lower wing skins and on the front and rear spars.

Also referenced in Chapter 1 of this thesis is [5.2] AC20-136, "Protection of Aircraft Electrical/Electronic Systems against the Indirect Effects of Lightning". This Advisory Circular is used by aircraft designers to guide the development of solutions for protecting electrical and electronic systems from the effects of lightning while also achieving successful compliance to applicable aviation regulations.

5.8.2 Corrosion Impacts on Indirect Effects Lightning Protection Schemes

In order to start the discussion of protection required for indirect effects lightning protection, it is appropriate to discuss corrosion and its effect on indirect protection. In most cases, dissimilar metals shall not be used in contact with each other unless protected against electrolytic corrosion. Electrolytic corrosion can be defined by several industry standards or by individual standards that are created by the design team assembled for creation of the aircraft systems and components. Structural components are often protected against corrosion in several ways including use of primer and Corrosion Inhibiting Compounds (CIC). The issue that needs to be resolved arises when the combination of corrosion protection, use of metals that when in contact generate, electrolytic corrosion and the need for long term current carrying capacity between the metals are combined into one requirement. Though design teams can select sources for design guidance when using different metals in contact with each other, MIL-STD-889 is on source for locating definitions of dissimilar metal electrolytic corrosion [5.31].

The most common type of corrosion which can affect electrical bonds is the oxidation of metallic surfaces. This kind of galvanic corrosion at the contact of two dissimilar metals and the degradation of materials over time used for shielding are important design constraints for which the methodology addresses. For good long term shielding, several variables should be considered. First it is important to use corrosion resistant metals within the design. A preferred electrical bond would be metal to metal bonding called a fayed surface bond. Additionally, corrosion protection should be provided for the metals selected. At times it may be most practical to interface metals of different types such as a nickel plated bond jumper to an aluminum structural member electrically bonding the avionic component to the ground plane within the aircraft. A large selection of surface finishes and corrosion prevention solutions are available. If the bond surface requires contact with Monel metal (alloy of Nickel 60%-70% and copper 20%-35% and a small amount of iron) or a tin coated steel RF gasket for example, tin or cadmium plated surfaces offer the best finish compatibility. If the bond path is critical to the lightning protection design, chromate type film treatment is often recommended. Chromate films can offer good protection against corrosion between a connector receptacle and an avionics controller for instance while also providing a good electrical conduction bond path between the two metals. The interface of dissimilar metals should be avoided when possible. When dissimilar metals are in contact and exposed to a corrosive atmosphere, galvanic action can destroy the electromagnetic shielding and bonding characteristics. In this case, sealants that provide both conductive and properties and environmental protection may be used. Metals are active when interfacing with other metals or different types. The advisory circular AC43.13, starting at Par 247, [5.55] briefly covers several types of corrosion and corrosion protection that may be applied when using metals of different anodic/cathodic properties.

The Galvanic Table reference 5-15 lists metals in the order of their relative activity in sea water environment. The list begins with the more active (anodic) metal and proceeds down to the least active (cathodic) metal of the galvanic series.
A "galvanic series" applies to a particular electrolyte solution; hence for each specific solution which is expected to be encountered for actual use, a different order or series will ensue. The sea water galvanic series included in this table is a comprehensive galvanic series taken from MIL-STD-889 [5.31]. For any combination of dissimilar metals taken from the galvanic table in Table 5-15, the metal with the lower number will act as an anode and will corrode preferentially.

	Active (Anodic)		Active (Anodic)		Active (Anodic)
1	Magnesium	32	Stainless steel 410 (active)	63	Monel 400
2	Mg alloy AZ-31B	33	Copper (plated, cast, or wrought)	64	Stainless steel 201 (active)
3	Mg alloy HK-31A	34	Nickel (plated)	65	Carpenter 20 (active)
4	Zinc (hot-dip, die cast, or plated)	35	Chromium (Plated)	66	Stainless steel 321 (active)
5	Beryllium (hot pressed)	36	Tantalum	67	Stainless steel 316 (active)
6	Al 7072 clad on 7075	37	AM350 (active)	68	Stainless steel 309 (active)
7	Al 2014-T3	38	Stainless steel 310 (active)	69	Stainless steel 17-7PH (passive)
8	Al 1160-H14	39	Stainless steel 301 (active)	70	Silicone Bronze 655
9	Al 7079-T6	40	Stainless steel 304 (active)	71	Stainless steel 304 (passive)
10	Cadmium (plated)	41	Stainless steel 430 (active)	72	Stainless steel 301 (passive)
11	Uranium	42	Stainless steel 410	73	Stainless steel 321

	Active (Anodic)		Active (Anodic)		Active (Anodic)
			(active)		(passive)
12	Al 218 (die cast)	43	Stainless steel 17-7PH (active)	74	Stainless steel 201 (passive)
13	Al 5052-0	44	Tungsten	75	Stainless steel 286 (passive)
14	Al 5052-H12	45	Niobium (columbium) 1% Zr	76	Stainless steel 316L (passive)
15	Al 5456-0, H353	46	Brass, Yellow, 268	77	AM355 (active)
16	Al 5052-H32	47	Uranium 8% Mo.	78	Stainless steel 202 (passive)
17	Al 1100-0	48	Brass, Naval, 464	79	Carpenter 20 (passive)
18	Al 3003-H25	49	Yellow Brass	80	AM355 (passive)
19	Al 6061-T6	50	Muntz Metal 280	81	A286 (passive)
20	Al A360 (die cast)	51	Brass (plated)	82	Titanium 5A1, 2.5 Sn
21	Al 7075-T6	52	Nickel-silver (18% Ni)	83	Titanium 13V, 11Cr, 3Al (annealed)
22	Al 6061-0	53	Stainless steel 316L (active)	84	Titanium 6Al, 4V (solution treated and aged)
23	Indium	54	Bronze 220	85	Titanium 6Al, 4V (anneal)
24	Al 2014-0	55	Copper 110	86	Titanium 8Mn
25	Al 2024-T4	56	Red Brass	87	Titanium 13V, 11Cr 3Al (solution heat treated and aged)
26	Al 5052-H16	57	Stainless steel 347 (active)	88	Titanium 75A
27	Tin (plated)	58	Molybdenum, Commercial pure	89	AM350 (passive)
28	Stainless steel 430 (active)	59	Copper-nickel 715	90	Silver
29	Lead	60	Admiralty brass	91	Gold
30	Steel 1010	61	Stainless steel 202 (active)	92	Graphite
31	Iron (cast)	62	Bronze, Phosphor 534 (B-1)	93	Noble (Less Active, Cathodic)

Table 5-15 Table of Metals in Galvanic Orientation

Galvanic series relationships are useful as a guide for selecting metals to be joined, will help the selection of metals that have the least galvanic interaction, or will indicate the need or degree of protection to be applied to lessen the expected potential interactions.

Generally, the closer one metal is to another in the series, the more compatible they will be, i.e., the galvanic effects will be minimal. Conversely, the farther one metal is from another, the greater the corrosion will be.

Notice that graphite is at the bottom of the table. The largest amount of corrosion potential in this table would be created if a large amount of graphite is interfaced with a small piece of magnesium and introduced into the salt water catalyst.

In a galvanic couple, the metal higher in the series (or the smaller the number on the table) represents the anode, and will corrode preferentially in the environment.

Metals widely separated in the galvanic series must be protected if they are to be joined. Appropriate measures should be taken to avoid contact. This can be accomplished by several methods:
Sacrificial - applying to the cathodic member a sacrificial coating having a potential similar to or near that of the anodic member. If you are designing for a sacrificial element, the sacrificial element should be on the anodic side and smaller. Cadmium plate (No. 10) on steel bolts (No. 81) holding 2024-T4 (No. 25) plates will sacrifice the cadmium instead of corroding the Aluminum. This is one reason for using new bolts that have the Cad plate intact.
Sealing - sealing a dissimilar metal interface to insure that faying surfaces are water-tight or free from potential moisture ingress. This technique should be used when designing bond jumpers made of a metal dissimilar to the attaching structure or grounding component in particularly harsh airplane environments outside the pressure vessel.
Resistance - painting or coating all surfaces to increase the resistance of the electrical circuit. Though this is a good corrosion prevention solution, it does not offer the best conductivity and is only used to prepare electrical bonds when a chemical conversion coating or a chromate (compatible metallic paint) is applied.

The (Non-Aerodynamic) Area Rule
To avoid corrosion, avoid a small anodic area relative to the cathodic area.

Corollary I - Use LARGE ANODE AREA.
Corollary II - The larger the relative anode area, the lower the galvanic current density on the anode, the lesser the attack.
Corollary III - The amount of galvanic corrosion may be considered as proportional to the Cathode/Anode area ratio.
Corollary IV - Design for a SMALL Cathodic/Anodic Ratio (CAR). (When designing, remember your small CAR.)
Corollary V - The same metal or more noble (cathodic, higher number in the table) metals should be used for small fasteners and bolts.

Sea Water Environments

Metals exposed to sea water environments shall be corrosion and stress corrosion resistant or shall be processed to resist corrosion and stress-corrosion. Irrespective of metals involved, all exposed edges should be sealed with a suitable sealant material conforming to MIL-S-8802. When non-compatible materials are joined, an interposing material compatible with each shall be used.

Non-Metallic Materials

Material other than true metals, i.e., non-metallic materials which must be considered as metallic materials, unless there is supporting evidence to the contrary. If these material are essentially free of corrosive agents (salts), free of acid or alkaline materials (neutral pH), and free of carbon or metallic particles, not subject to bio-deterioration or will not support fungal growth, and do not absorb or wick water, then these may be considered non-metallic and suitable for joining to metals. Many materials classed non-metallic will initiate corrosion of metals to which they are joined, e.g., cellulosic reinforced plastics, carbon or metal loaded resin materials, asbestos-cement composites.

More Precautions for Joining

Where it becomes necessary that relatively incompatible metals must be assembled, the following precautions and joining methods are provided for alleviation of galvanic corrosion.

1. For Electrical Connection - Select materials which are indicated to be more compatible in accordance with the galvanic series.
2. Design metal couples so that the area of the cathode is smaller (appreciably) than the area of the anodic metal. For example, bolts or screws of stainless steel for fastening aluminum sheet, but not reverse.
3. Interpose a compatible metallic gasket or washer between the dissimilar metals prior to fastening.
4. Plate the cathodic member with a metal compatible to the anode.
5. Select an electrically conductive sealant.
6. Not For Electrical Conductors - Interpose a non-absorbing, inert gasket material or washer between the dissimilar materials prior to connecting them.

Other Approaches to Conductive Interface Assembly

Seal all faying edges to preclude the entrance of liquids. This can be a problematic approach if the sealant traps moisture in the electrical bond interface. Designs of these type bonds need to consider alternatives when in severely moist and harsh environments.
Apply corrosion-inhibiting pastes or compounds under heads of screws or bolts inserted into dissimilar metal surfaces whether or not the fasteners had been previously plated or otherwise treated. In some instances, it may be feasible to apply an organic coating to the faying surfaces prior to assembly. This would be applicable to joints which are not required to be electrically conductive.

Where it will not interfere with the proposed use of the assembly, the external joint should be coated externally with an effective paint system.

It is important to spend some time dwelling on the importance of material compatibility when discussing long term effectiveness of indirect lightning protection. The following photos provide typical examples of connector testing results when exposing different connectors to a corrosive environment.

5.8.3 Bonding for Indirect Effects Protection against Lightning Induced Transients

The electromagnetic fields inside the aircraft in these case studies that occur as the result of a lightning strike are higher in areas of the aircraft where composite structures are used than in the other aluminum airframe sections. The higher electrical field strength requires increased protection of signal and power wiring to reduce the induced transients to levels compatible with Line Replaceable Unit (LRU) designs located underneath the composite structure panels.

Wiring shields (added wire included in the wire looms for the sole purpose of carrying the current resulting from a lightning strike) that have been designed with reliable low resistance grounding at both ends provide a reduction of the induced current and voltage levels on the power and signal wires that will be imposed on the LRU inputs. This protects the LRUs by reducing the electrical transients that enter the equipment through the wires. Properly grounded shields reduce these transients to levels specified by the wire installation design group for equipment qualification.

The equipment test levels specified in the aircraft design documentation assume that shielding is properly installed with both ends properly grounded in the airplane. Due to test equipment limitations, testing is typically conducted with lightning levels that would be present at the equipment after attenuation by shielding, therefore the testing is conducted with shield grounds disconnected.

In the event that equipment wiring is installed without proper shield ground paths that remain effective for the life of the airplane, the equipment must be designed and qualified for much higher applied transient levels or scheduled maintenance would be required to insure the effectiveness of the shield grounding is maintained. This body of work establishes a methodology for use during design of an aircraft to ensure the long term availability of lightning protection has been included in the design decision making process.

Careful design considerations must be used on the entire shield ground path for the aircraft and its equipment. One critical area is the grounding of the connector receptacle to its mounting surface on either a bracket used at production breaks or an LRU or sensor. The interface between the connector and LRU or bracket or panel surface on which it is mounted must meet all requirements for cleaning and conductivity that are needed for a fayed surface electrical bond. Depending on the environment of the installation, protection of the joint must be provided to insure the joint electrical conductivity does not degrade over time with exposure to the environment. The OEM approved process for mounting bonding connector receptacles is (specification number retained) which is described in by the OEM electrical design documentation. While this specification is usually not directly imposed on LRUs manufactured by outside suppliers, similar robust designs with attention to proper surface galvanic compatibility, preparation, and protection must be employed in the manufacture of their equipment.

The best approach for wiring shielding used for lightning, HIRF, and EMI is terminated either circumferentially or "zero length" meaning no use of a bonding lead (extension wire) on the backshell of the connector. It is very important that the ground or earthing path that provides for the protection including the shielding is not compromised. To insure robust installation that is effective for the life of the airplane, all electrical connector interfaces in a lightning path are identified in the design documentation as a “designated bond” or “designated ground”, measured for compliance upon installation and have a resistance value called out on model based definition or controlled by approved process specification.

5.8.4 Connectors and Bonding for Indirect Effects Protection

Connectors and the interconnecting wire looms deploy bonding and grounding technologies and material selection to ensure long term installation availability.

Typical connector lightning protection designs consist of the connector assembly as shown in Figure 5-48, including a buildup of a tin or nickel plated copper shield, a back shell, a plug, a receptacle; all made of several potential material types and a bonding design to the LRU such as a fay surface electrical bond interface.

Example 1 (OEM Part number retained) Stainless Steel, Series III, MIL-C-38999 connector
Design:

- Same panel cutout as most existing connectors
- Accommodate standard, coax, twinax and quadrax contacts
- Self-locking with approximately a 360 degree coupling turn
- Environmentally sealed
- 200 C maximum operating temperature
- 300 V Comparative Tracking Index (CTI – determines spacing between pins)
- Withstand 6.0 KA peak of indirect lightning strike
- Resistant to potassium formate runway deicing fluid
- Performance requirements
- 3 milliohm, shell to shell resistance
- 10 milliohm, shell to shell resistance

Figure 5-48 General purpose stainless steel connector MIL-C-38999

Example 1 Application:

The example provided below may be used to control an APU Inlet Door Actuator. This installation is made up of a circular SS connector and nickel plated composite back shell using a pull through shield termination. A typical lightning protection scheme is shown in Figure 5-49. The connector has an internal Nickel coated copper over braid cable ground lead that is retained with a Stainless Steel (SS) clamp and it is terminated at the connector self-locking back shell. The connector is attached to the passivated stainless steel (CRES) APU Inlet Door Actuator enclosure secured via 4 passivated CRES screws, and 2 alodine aluminum self-locking nut plates with primer. Screws are to be tightened with torque of between (torque value retained) in-lb. A simulated installation including a LRU and mounting bracket is shown in Figure 5-50.

Example Bonding and Grounding scheme and build-up:

This device is grounded using a bond jumper that is attached to the APU Inlet Door Actuator on one side, and then attached to an anodized aluminum bracket on the other side. The APU Inlet Door Actuator has a pre-installed ground stud installed below the connector where the bond jumper will attach. The anodized aluminum bracket is then attached to a horizontal stiffener of the firewall. The bonding jumper terminal on the APU Inlet Door Actuator is installed per OEM installation specification (retained). The bonding jumper terminal is attached to the aluminum bracket per OEM installation specification (retained) including sealant.

The pre-installed ground stud is made up of the following per OEM electrical installation specification (retained):

1. Passivated CRES screw
2. Passivated CRES lock washer
3. Passivated CRES washer
4. Passivated CRES washer
5. Passivated CRES nut

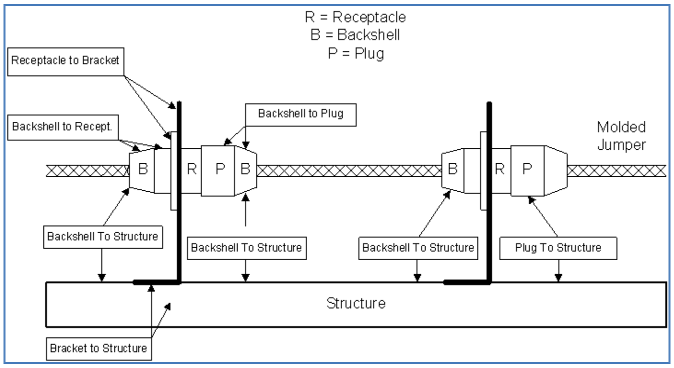


Figure 5-49 Connector and wire loom bond path to structure (typical)

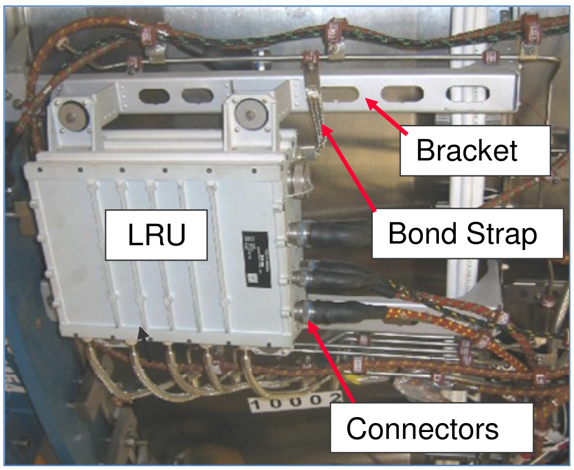


Figure 5-50 Typical LRU installation with connectors, wiring and grounding

Figures 5-51, 5-52 and 5-53 provide typical examples of connector testing results when exposing different connectors to a corrosive environment.


Figure 5-51 Connector test preparation

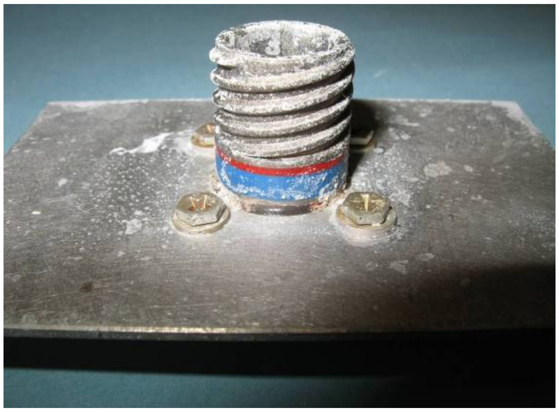


Figure 5-52 Connector Receptacle Corrosion in test rig

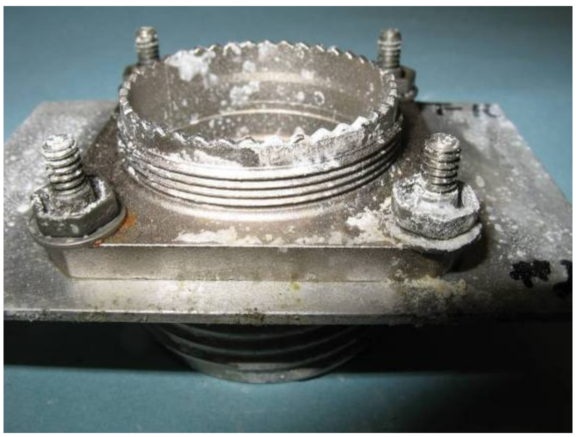


Figure 5-53 Connector Fastener Corrosion in test rig

To demonstrate the methodology for lightning protection continued airworthiness design against the indirect effects of lightning, one of the case studies examines a connector on the Auxiliary Power Unit (APU). Indirect lightning effects protection is provided to aircraft equipment through the use of shields within wire looms, connection to the back shell and through the connector plug to the LRU receptacle and finally to the aircraft ground plane through use of an electrical bond between the LRU and the aircraft structure. If the aircraft structure is composite, it may be necessary to attach the LRU to metal structure on the aircraft through use of a bond jumper (wire). In all cases for continued effectiveness of protection against the indirect effects of lightning, it is important to make sure that electrical connectivity is maintained within all aircraft environments. For this, it is important to understand the installed environment and account for conditions within the aircraft operations that could cause degradation of the protection. Corrosion is often not considered in any detail at the time of original design since the installation of the indirect effect protection is tested at the factory before delivery to ensure that the appropriate electrical bond is in place. Unfortunately, the continued availability of the electrical bond may be degraded by moisture, vibration, chemical exposure or excessive heat cycles. In-direct effects protection is a passive feature of the installation that does not provide any indication whether the protection is degraded at a later point in time. Since the loss of protection can result in a potentially catastrophic or hazardous condition given the occurrence of an untimely lightning strike event, this degradation is important to evaluate at or prior to the design conclusion.

With the application of the proposed methodology, past experience is combined with a scientific evaluation of the effects of environment on the protection scheme. With past experience captured in reports to the manufacturer by airline customers technical staff and independent testing conducted through technical lightning protection assurance tests, an aircraft manufacturer can collect important information to share during the detailed design phase. Some of the designs that may cause concern for the continued airworthiness of in-direct lightning protection are as follows:

1. Tin plated shield wires erosion of tin plating outside the pressure vessel
2. Cad plated connectors in the landing gear wheel wells
3. Nickel plated aluminum connectors in areas with moisture and significant temperature fluctuations
4. Tin plated copper braided bond jumpers in moisture prone areas
5. Bond jumpers of any type deployed in locations where the bond jumper moves (bending cycles) in moving control surface applications (wings, stabilizers etc.)

Lightning designs for indirect effects protection are evaluated after the aircraft is assembled and the direct drive tests are performed. These tests are accomplished after the aircraft is assembled in order to assess whether adequate dielectric breakdown is provided by the designs. The data from these ground tests shows that the induced lightning protection design for the (aircraft type reference retained) reduces induced voltage transients on all critical and essential system wiring to levels below which the systems were qualified in the laboratory. In a majority of cases where the test results were compared to theoretical values established in the design simulations, much larger than required margins were achieved on the final designs physical implementation.

During the first OEM test on this aircraft type accomplished after the aircraft was assembled, some higher than expected transients were found on the following LRUs: (LRU references retained). The major problem was identified at that time to be related to non-terminated shields at the equipment end. This design characteristic is not expected to be present at the time of the preliminary design phase but rather manifest at a much later stage in the development program. The affected equipment groups redesigned the appropriate wiring to include proper terminations and a test was conducted after the redesign was accomplished. The test aircraft was then retrofitted with the re-designed wiring and a re-test was conducted to ensure that the redesigned wire shielding was adequate. Peak voltages were collected to compare to the designed voltage expected due to a lightning strike.

Some measurements were taken with the external LRUs installed in a production configuration. In this configuration, the dielectric strength of the external LRU is used to absorb some of the lightning transient energy. In all cases, the known dielectric breakdown strength of the external LRU is larger than the measured induced voltage across the dielectric generated by the lightning strike. Therefore, the dielectric will not break down during a lightning strike and will be able to withstand that portion of the induced transient across the LRU connector interface. Note that the dielectric breakdown strength of these external LRUs will require tracking of the protection effectiveness in service to ensure the lightning shielding of the aircraft does not deteriorate with time.

Two test points had non-conductive connectors at the external LRU. These connector LRU designs passed certification testing in this configuration. However, a 6 inch bond wire was added to each non-conductive connector installation after certification testing was complete. These bonding wires “pigtails” are considered an extra layer of protection on top of the already certified aircraft shielding design and require additional evaluation for the continued effectiveness suggested in this body of work. As this case study has demonstrated, the continued design improvement and adjustment of in-direct protection requires continuous evaluation for airworthiness years after the aircraft is in service.

5.8.5 Case Study for Indirect Effects Lightning Protection on Electronic Equipment

The following electrical and electronic lightning protection components have been selected as case studies for the methodology contained in this work.

APU (Equipment reference retained) Equipment, Shields and Connectors

The selection of electronic system equipment protection to aircraft structure listed above evaluates typical lightning protection schemes used in the industry. Protection of electronic equipment are often accomplished with shielding contained in wire looms and electrical bonds of the equipment using the metallic outer case of the equipment and bonding this to the aircraft structure by either a mechanical fastening system or a bond “jumper” wire that attaches the equipment on one end and to the structural ground on the aircraft structure. Different techniques are used in different designs that may offer more than a single bonding scheme to evaluate. At the initial stages of the design process, it is not adequate to simply know the type of connectors, shield wires (also called “shields”) and equipment metallic material. In wire installation designs, it is possible to allow equipment to remain ungrounded while providing ground paths through wiring interfaces with other connected equipment. It is important in this evaluation to consider the final installation design early in the design process in order to provide the most effective bonding practices and ensure that late design changes that may be recommended from the assessment sheet analysis are minimized. The (aircraft type reference retained) wiring approach provides sufficient wire shielding to protect the (aircraft type reference retained) systems from electromagnetic environments such as HIRF or lightning over normal operating frequency ranges. The wire loom shielding exists in addition to LRU box protection in most cases as described in this paragraph. The (aircraft type reference retained) wire shielding baseline design is to shield all wiring external to the pressure vessel with one layer of shielding and terminate both ends of the shield with a 2 inch pigtail to the connector back shell. Details of this termination and design will be included in the assessment sheets. The only exceptions at the time of the design were for wiring in the air conditioning bay and wheel wells that are routed near the bays. For these wires, shielding was added on a case by case basis during design discussions that considered the geometry of the wire routing. In addition, all wires associated with a critical system and within close proximity of the flight deck windows have a single layer of shielding with the shield terminated at both ends with a 2 inch pigtail to the connector back shell.

Wire routing has significant effect on the total coupling characteristics of the electrical system. Basic principles have been established within the wire route designs to reduce the effects of interconnecting wires that cause unwanted coupling [5.53].

In general, the closer that a conductor is to a metallic ground plane, the less is the flux that can pass between that conductor and the ground plane. Magnetic fields are concentrated around protruding structural members and diverge in inside corners. Hence, conductors located at the top of protruding members will intercept more magnetic flux than conductors place in corners where field intensity is weaker. These principles may be used when deciding the most appropriate locations for placing wire looms. Fields will be weaker on the interior of a u-shaped member than they will be on the edges of that same member. Fields are also lowest inside the closed member; however, even a trough shaped member will provide more shielding than wires located on the exposed edge. Wiring locations are important to the amount of in-direct effects a lightning strike can cause on system operations. Wires should be located away from apertures whenever possible.

Case Study 1 System Protection – APU Electronics Case Study and Assessment Sheets

Following are a series of lightning protection examples from the (aircraft type reference retained) aircraft design. The examples used in the assessment sheets provide a means to test the methodology proposed by these case studies. Each design alternative below represents a unique aspect of lightning protection designs. The case studies are performed in order to test the methodology against a set of very different lightning protection components. Indirect effects protection and direct effects protection are both included in the case studies.

Engineering L/HIRF Protective Device Assessment Sheet
Protection Component Name

APU (LRU name retained) equipment, shields and connectors

Section 1. Lightning/HIRF Protection Component Data	
Assessment Sheet Number	SYS001 (STR=Structures, FUL=Fuel, SYS=Electrical/Electronic Systems, ANT=Antenna)
Engineer Name:	Bill Bozemann
Part Number: Connector MS3459LS12S-3P	(Part numbers and references were either retained or revised to imaginary numbers to protect proprietary

	information) Oil temperature Sensor X1 on the Auxiliary Power Unit. The sensor attaches to the YY200 connector mounted on the FF1000 bracket. The FF1000 bracket is the pressure seal at Station XYZ location. The YY200 connector on Bracket FF1000 (Stabilizer Trim Compartment Bulkhead): Connector equipment number(s) on wire loom BB000: YY200J (Max Impedance value = 11.0 milliohm) Wire diagrams: (reference numbers retained).
Manufacturer:	Tesela Industries (OEM Names retained)
Lightning Zone	Zone 2
Design Service Life Goal:	Design for protection of the APU LRU from the indirect effects of lightning strike that may cause lack of proper APU speed control and subsequent APU turbine “run away”. Loss of over-speed protection and un-commanded fuel flow increase could cause uncontained APU failure, which compromises pitch control. Inspections and repairs are not required after a lightning strike event unless lightning strike affected APU operation during flight or the lightning strike direct effect evidence shows some secondary damage effect to the APU LRU case, wire looms or ground jumpers. DESIGN CHARACTERISTICS (Connector and wiring) • Medium to heavy weight cylindrical • MS345( ) series inter-mateable with existing MIL-DTL-5015 solder or crimp versions on existing equipment • Captive coupling nut mechanism, utilizes retaining rings in combination with “L” washers to prevent inadvertent disassembly • Multiple interlock systems ensure permanent insert retention • Positive control of dielectric separation with guaranteed ease of contact insertion • Positive contact retention provided by a close tolerance damage-proof metal retention clip • Completely sealed against environmental extremes with: • individual contact seals (conical risers on pin interface)

	• interfacial seals between contacts • peripheral gasket shell-to-shell seals • redundant rear wire seals and insert-to-shell seals
Date: November 16, 2009	

Section 2. Component Description System Criticality

System Criticality: Critical

Description:

Analysis of the lightning protection for the APU LRU (LRU name retained) will center on the shields and connector designs on wire loom between the APU Oil Temperature Sensor mounted on the APU and APU fire wall. This engineering assessment will examine the specific design of the X1 Connector on the APU which connects to the connector (equipment number YY200) on APU firewall disconnect bracket FF1000. The wire loom is attached to the X1 Oil Temperature Sensor on one end and to YY200 connector on the other end at the fire wall bulkhead bracket FF1000. The X1 connector is an industry standard part number MS3459LS12S-3P. The MS3459LS12S-3P (also called Class LS) is a passivated stainless steel connector with a fluid resistant insert. The wire loom has a round Nickel-Coated Copper shield that is terminated at the Stainless Steel (SS) saddle clamp and secured through SS fasteners. The round SS connector back shell is attached to the common industry part number P/N MS3459LS12S-3S SS connector plug. The connector plug has a common industry part number P/N M39029-30-217 contact pin/socket. The SS connector plug, through a self-locking thread and a guided pin, is mated to the common industry part number P/N MS3459LS12S-3P receptacle, which is welded to the SS X1 sensor. The SS sensor is attached to the APU housing through a Copper squeeze washer and locked in place through a SS lock wire.

Temperature:

Class LS connector has a temperature range of –55℃ (–75℉) to 200℃ (392℉)

Durability:

Minimum of 100 mating cycles.

Section 3. Component Purpose and Operational Theory

The APU LRU controls the APU operation when the LRU receives a signal from the controls in the flight compartment. The LRU is in the aft cargo compartment right side. The LRU is on a shelf in the aft cargo compartment near the aft cargo door. The LRU is a line replaceable unit (LRU). The circuit cards in the LRU are not individually removable. To get access to the LRU, you must open the aft cargo door and remove the panel that protects the LRU front face.

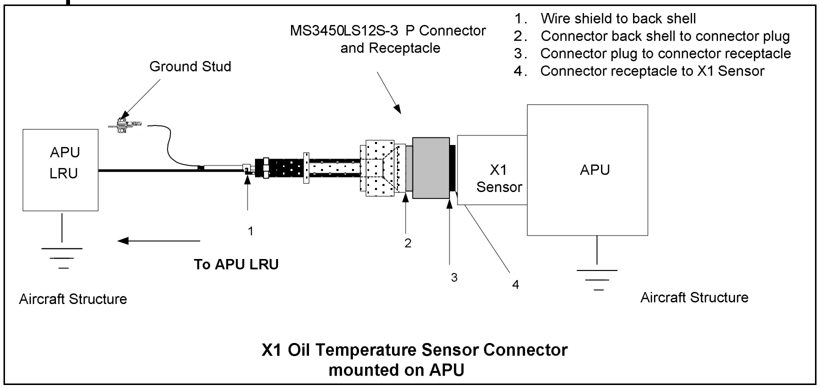
If you remove the LRU for maintenance, do not remove the data memory module from the APU at the same time. Loss of APU memory data will result.

Connectors associated with the APU LRU are selected by the supplier and installed both on the aircraft and on the APU. The LRU controls APU functions. The LRU also contains circuits for fault detection and isolation.

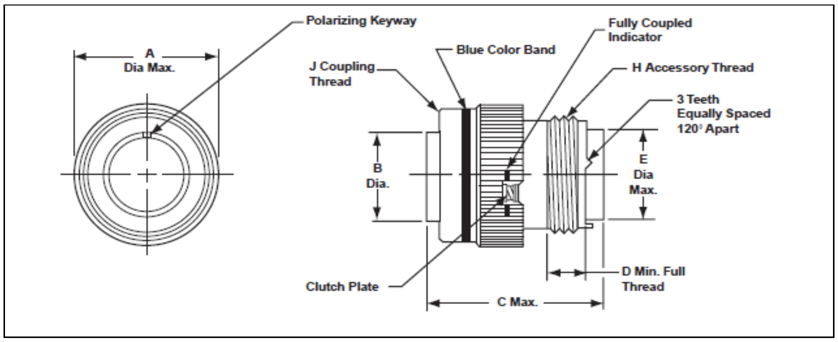
The LRU uses signals from certain APU and airplane systems for correct operation of the APU.

Section 4. Component Schematic and Installation Details

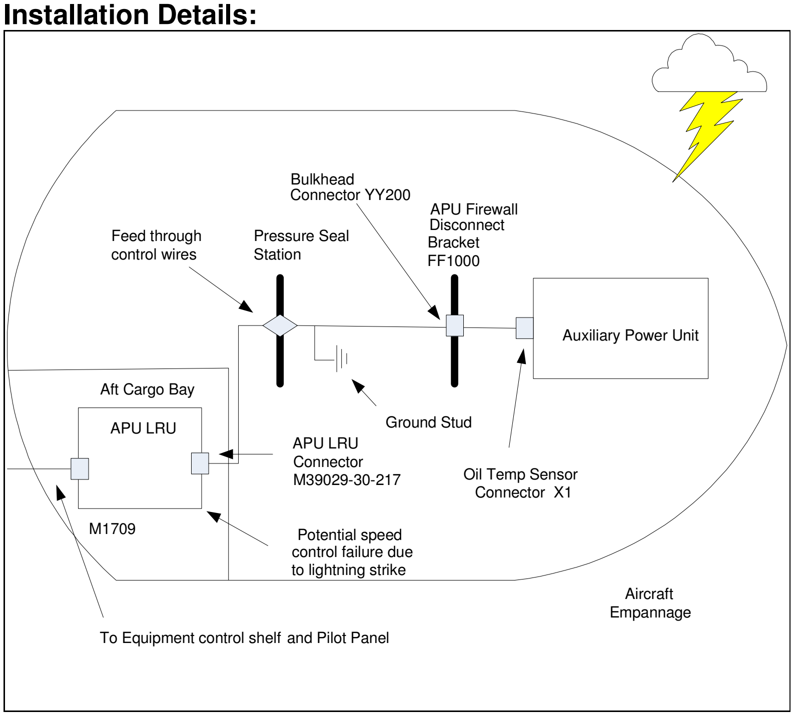
Component Schematic:



Connector detail - MS3459LS12S-3P



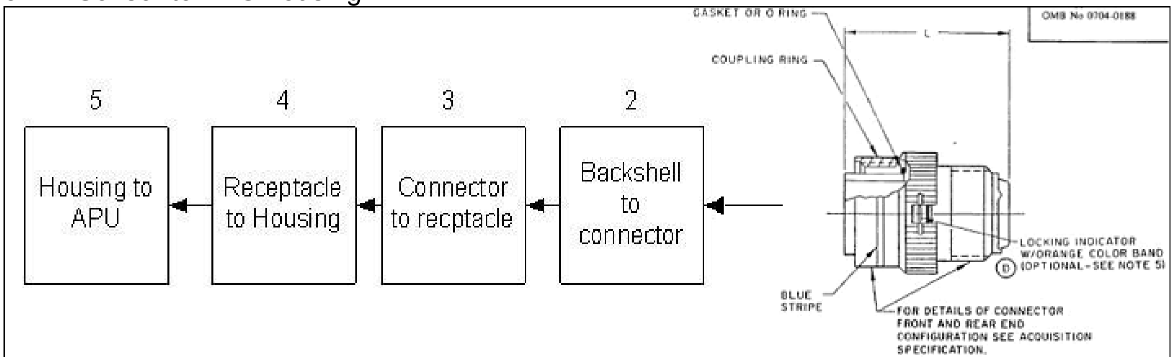
Installation Details:



For installation locations and graphics see case study Figures 5-54 and 5-55.

Bond Path Providing Protection:

1. Wire shield to back shell
2. Connector back shell to connector plug
3. Connector plug to connector receptacle
4. Connector receptacle to X1 Sensor
5. X1 Sensor to APU housing



MS3459 plug with self-locking coupling nut

Section 5. Installation Environmental Threats

The APU X1 Oil Temperature Sensor is installed outside the pressure vessel and exposed to multiple environmental threats.

Description of installed environment:

The installation is outside pressure vessel and exposed to severe temperature changes, contamination, moisture, and vibration. In general, the installation environment is protected from direct contact with environmental threats outside the aircraft since the APU installation is contained within the empennage and operated with APU doors closed when in service.

Flammable Leakage Zone Description and Protection:

The empennage of the aircraft contains the Auxiliary Power Unit which is serviced with fuel through a concentric fuel feed line. This area is considered a fire zone due the presence of flammable fluids and is required to contain fire suppression and warning systems. In addition, the presence of potential for fire in this area requires that lightning protection components such as shields inside wire looms be able to sustain high temperatures in accordance with the wire design guides for flammable leakage zones.

Ratings of environmental threats:

Location: Nose Radome Exterior		
Threat Type	**Rating of threat**	**Installation**

	severity in this location (High, Medium, Low)	resistance to degradation (High Medium, Low)
System Operating Fluids (oil, hydraulic fluid, Grease and Lubricants)	Low	High
Chemicals and Applied Fluids (cleaning fluids, fire retardants, de-icing, wing anti-ice fluids, liquid cooling)	Low	Medium
Natural Occurring Fluids (condensation, precipitation, humidity, ice, rain, snow)	Medium	Medium
Temperature Exposure (swings in temperature, and extensive exposure to extreme high or low temperatures)	Medium	High
Vibration (low or high frequency vibration)	High	Medium
Fuel (Exposure to fuel)	Low	High
Flammable Leakage Zone (Yes/No)	Yes	High

Section 6. Assessment of Critical Characteristics in the Installed Environment

The continued airworthiness of associated components within the lightning protection designed bond path is expected to perform the function of providing indirect lightning current protection during all operating phases of the aircraft flight profile. The need for protection to the X1 connector and wire loom is due to the potential for a lightning strike event to cause upset to the APU LRU. This upset to the LRU could have a subsequent effect on the ability of the LRU to avert a potential over speed condition. Over speed logic contained within the APU LRU is provided by the LRU software and may be adversely affected if a lightning strike current exceeds appropriate voltage “stand-off” requirements of 600 Volts. To provide lower voltage threats during a lightning strike event, the connector associated with the X1 Oil Temperature Sensor must maintain a low impedance path to the aircraft structure during a lightning strike event. The MS3450 connector and shield design must be proven by test or in-service performance to maintain low impedance. Material interfaces between the connector components, wire shield and sensor must be compatible and resistant to the effects of corrosion over time in this moisture-prone environment. The connector exterior shell is passivated stainless steel.

The passivated stainless steel exterior of the connector body is an excellent choice to reduce any corrosion associated with the external environment. Component interface metals associated with the protection bond path are found to be compatible. SS connectors and associated components have performed "Excellent" in the APU environment based on a history of NO galvanic or EMI difficulties with MS3450 series connectors in previous OEM applications. Self-Locking connectors have no torque requirement and achieve fully locked position when ratcheting the connector until visual indicators line up and the connector bottoms out. The

performance is expected to be less than optimal based on the lack of a ground spring assembly within the connector, which makes shell to shell conductivity sensitive applications with a high vibration installed environment.	
Section 7. Test Plan Input	
MS3450 series connectors require specific testing to ensure that the installed environment will not degrade the connectors below acceptable bond path resistance limits. These connectors have been successfully used in aerospace for many different applications. In the application of these connectors on the APU Temperature Sensor (X1), the testing should include an appropriate level of vibration to determine continued conductivity across the connector after prolonged installation. Temperature and moisture should also be applied during the test to simulate actual installation in the moisture prone environment.	
Section 8. Test Data Results	
Tests for this installation have been accomplished by similarity to other past OEM designs. As a result, additional testing for this application is not necessary. Qualification testing at the time of the part design conformity is adequate. In testing performed on other aircraft applications after a period of service experience, OEM Engineering has found that this sensor connector does not pass the loop resistance test requirements in the L/HIRF Protection Assurance Validation Test Procedures. Assurance test data on the X1 connector shows that after (flight hours retained) two loose plugs were found exceeding the factory resistance values between the connector plug and receptacle. The task was accomplished three times with two findings. It is estimated that the packing material inside the connector relaxes over time and without the advantage of a ground spring assembly to ensure continued excellent electrical conductivity that the plug shell to receptacle shell on the temperature sensor unit conductivity deteriorates.	
Section 9. Report from Test Engineer Regarding Continued Airworthiness	
Test Engineer Name:	B. Billings
Report: **(include significant findings and relevance to continued airworthiness)**	**Lightning strike protection effectiveness**: Qualification testing of this connector passed lightning current transfer requirements. However, past testing in the field has proven that high resistance values may be present after an indeterminable service duty. Application of this connector design is expected to degrade to an unacceptable degree over the life of the connector installation. Testing on aircraft in operation has exposed several (actual number of failures retained) high resistance failures. Though only a few tests have been conducted with high resistance resulting from poor electrical conductivity across the connector receptacle and the connector plug interface, extrapolation of the few high resistances identified in service would imply that many

	more aircraft suffer from the same deteriorating conductivity associated with the connector part number MS3450 type connector. This test result directs the design team to consider an alternative connector or minimize application of this connector within design solutions. A qualitative and destructive test of connectors demonstrating high resistance after use in service has not been performed.
Section 10. Design Revision Request	
The OEM recommends three possible alternatives to application of this connector type on critical systems. 1. Perform an evaluation of a degraded connector to determine the root cause of the connector degradation with subsequent solution determination based on findings. 2. Perform a modification to the wire looms that use the MS3450 type connectors to add an alternative electrical bond path across the connector plug and connector receptacle. 3. Use an alternative connector (connector part number retained) plug in later designs to avoid loss of electrical connectivity caused by lack of spring fingers in the MS3450LS12S-3P connector interior.	
Section 11. Revision accepted by Program	
Yes – The program suggests an investigation of this connector using a destructive test to determine cause followed by a resolution plan for application of these connectors.	
Section 12. Description of Final Optimized Design	
Action Taken: OEM recommends replacing this connector with a similar but superior performing connector. Use of connector part number (retained) should prove to perform much better in continued electrical bonding due to addition of "spring fingers" within the connector. The spring finger design is expected to allow the connector to sustain high vibrations and experience minor loosening while at the same time, allowing the spring fingers to maintain conductivity.	
Approval:	
Mr. G Sweers, Lightning Protection Analyst	Original Signed
Mr. Keith Smith, Lightning Protection Designer	Original SignSigneded
Mr. Jacob Owen, Bonding and Earthing Engineer	Original Signed
Mr. John Taylor, Chief Engineer	Original Signed

Figures attached to Assessment Sheet for APU Electronics

The following graphics are collected for use in the assessment of the lightning protection. These graphics were used to identify key component attributes contained within the assessment sheets.

Proprietary Graphic Retained

Figure 5-54 APU LRU location – aft cargo bay right side

Proprietary Graphic Retained

Figure 5-55 Auxiliary Power Unit Location and Oil Temperature Sensor Connector

5.8.6 Bonding and Grounding (Earthing) for Lightning Protection

Electrical bonding is the process of joining together by low resistance path(s) two or more objects or materials which are conductive or which have conductive surfaces so that they become an electrically conductive entity. Most often the processes involve the preparation and joining of faying surfaces of the abutting parts. The resultant entity may serve as a current return path but more generally, where it is the conductive structure of an aircraft or aerospace vehicle, it forms an electrical voltage-reference-plane which serves many purposes.

Electrical earthing (grounding) is, in general, the process of intentionally connecting an item to an electrical ground path (such as a wire, busbar, or chassis), or to an electrical reference-plane (such as earth or the electrically bonded structure of an aircraft/vehicle).

However, as used here the term “electrical ground” specifically refers to those connections made to an electrical reference-plane which are current return paths for power circuits (including the neutrals for three-phase power).

Electrical bonding and grounding are important for they have an effect on all the following design considerations:

- The performance of electrical power systems
- The control of: electromagnetic interference (EMI), electromagnetic pulse (EMP), and electrostatic voltages
- Protection against lightning effects
- Prevention of personnel shock and explosion.

An aircraft designer selects the proper means of bonding and grounding. In order to create acceptable design solutions, one must understand detail information on materials and methods used to achieve good bonds and grounds.

Electrical bonds designed and fabricated in accordance with good design practices established be aircraft manufacturers will meet or exceed the performance requirements of MIL–B–5087 [5.27]. Detailed exceptions to MIL–B–5087 requirements may be generated by an aircraft manufacturer to address special cases for any preferred design approach associated with the bonding method.

5.8.7 Definitions of Bonding and Grounding (Earthing) Terms

In order to organize requirements for bonding, classes for unique bonding approaches are defined for each bond type. Each class has an associated “Name” as found in Table 5-16 and description that is required for proper implementation of the methodology within a design theater. These bonding classes are created by the aircraft manufacturer and proposed as a center of excellence for meeting continued airworthiness criteria goals. Terms associated with bonding expertise are contained in this chapter Appendix B - Definition of Terms Used in Electrical Bonding and should be a required expertise for individuals affecting the design decisions on a new aircraft design program. *Class designations have been changed to retain OEM designations for bonding classifications.

Table 5-16 describes the bonding classes.

Class*	Name	Description
1	Antenna Installation	Antennas which require a homogeneous counterpoise or ground plane need a full faying surface bond to primary structure. Antennas with an integral counterpoise, such as radar scanners, require a bond between the waveguide or coaxial cable connector shell and the counterpoise on the equipment.
2	Current Return Path Ground	A ground path is the current return path required to return the current of an electrical circuit wire through a bonded wire terminal and through primary structure to the power source.
3	Shock Hazard	To eliminate personnel hazards, all exposed conductive housings of equipment containing electrical circuitry must be bonded to structure.
4	Lightning Protection	To prevent the ignition of flammable vapors and structural damage, lightning protection must be provided at all possible points of lightning entry into the vehicle. This protection must be proven adequate by testing.
5	RF Potential	To reduce R.F. radiation and interference effects, equipment which is susceptible to or radiates R.F. energy must be connected by a low impedance bond to structure. This includes wire and cable shield terminations.
6	Static Drain	To eliminate static interference, all isolated conducting items (except antennas) which have any linear dimension greater than 3 inches and which: • are exposed to the external airstream, or • carry fluids in motion, or • are subject to frictional charging, must have a low resistance bond to structure.
7	Fire/ Explosion Hazard	To prevent the ignition of flammable vapors, electrical equipment located in explosion hazard flammable leakage areas must be bonded to structure by providing a low resistance bond from the equipment case to structure.

Table 5-16 Bonding classifications for the design of an aircraft

For Class 4 lightning protection, bonding paths must be able to conduct up to the industry standard 200,000 amperes of current in many locations (locations ampere ratings are determined by the lightning zone map created by aircraft lightning threat model for design purposes) and must also protect nearby parts by presenting a low impedance path to ground path for current to conduct. Desirable characteristics of such a bond path are to create the most direct and robust bonding solution. Soldered joints in high current lightning bond paths are not acceptable since they do not resist damage during the high current event. The lightning protection design must also be proven by adequate testing at some point in the lightning protection design development. This could be a test that was conducted on the specific lightning protection design on a prior aircraft design project or could be conducted on a similar design where the design is certified by the regulatory authorities through a similarity assessment.

Lightning protection ground paths are designed into aircraft architecture to:

- Prevent malfunction of flight critical systems
- Prevent structural damage
- Avoid electrical breakdown or electrical heating damage to equipment
- Prevent sparking or arcing in Fire/Explosion Hazard Areas
- Prevent damage to non-conducting materials caused by generation of heat and mechanical forces from lightning discharge.

The design objectives used to create the required current path installations are drafted by the design community for use by several design groups. Current waveforms and threats from lightning are determined by industry standards such as the [5.28] Society of Automotive Engineers (SAE) Aerospace Recommended Practices (ARP) 5412 where the lightning environment waveforms are defined. Protection objectives can include several combined impacts associated with lightning protection function such as:

- Prevent electrical or electrical heating damage to equipment
- Control voltage drops within flight vehicles to a acceptable level
- Prevent sparking or arcing caused by poor conductive path designs
- Prevent damage to non-conducting materials caused by generation of heat, and mechanical forces from lightning discharge.

Flight equipment also requires appropriate lightning protection. This protection is provided to ensure that the vehicle flight characteristics and safety, crew visibility, and equipment performance take precedence when exposed to a lightning event. To ensure that the aircraft continues to operate safely throughout a lightning event, it is important that each external, conducting object, excluding antennas, which protrudes above the vehicle surface, must have an electrical bond to the vehicle skin, structure or designed ground plane on the aircraft. The external surface of each large non-conducting projection essential to flight or housing personnel (e.g., vertical stabilizer parts, wing tips, astrodomes and canopies) must have a lightning path to the vehicle skin. The vehicle skin is an important part of the lightning event protection as it provides for the Faraday cage that keeps much of the lightning energy on the surface of the aircraft structure. If a high-resistance surface coating is used as the lightning path on a structural component, the path-to-skin voltage at any point must be less than the breakdown voltage to any grounded object within the protected zone in order to ensure that an arc is not created.

Where protective conductors are shielded by insulating material or metal structure, and are not subject to a direct lightning strike, designers must decide on the current carrying capacity requirements for these conductors. In many designs, the cross sectional area must be equal to or larger than 6,530 circular mils (No. 12 AWG) for copper, or 10,380 circular mils (No. 10 AWG) for aluminum in order to meet the potential current flow capacity criteria. When protective conductors are installed on the external surface of the aircraft and are therefore exposed to a direct lightning strike, a minimum of 20,820 circular mils (No. 7 AWG) may be required for copper, or 33,100 circular mils (No. 5 AWG) for aluminum.

These protective conductors are sometimes called bond jumpers or earthing conductors and are discussed in more detail within the case studies. Figure 5-56 shows the design of a specific bond jumper. These bond jumpers can be either flat and braided or round. Some bond jumpers have a protective sleeve and others do not. Bond jumpers are typically made of copper with an outer coating such as tin or nickel to protect the jumper from oxidation. When designing a bonding scheme, it is important to identify these characteristics of the bond jumper in order to ensure that materials that interface with the bond jumper terminals are compatible and provide for proper sealant where necessary. The engineering assessment sheets are designed to address this issue properly during the aircraft design phase.

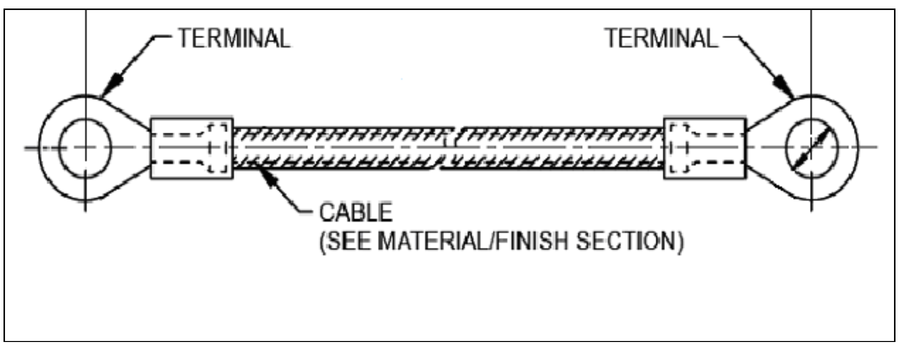


Figure 5-56 Typical Bond Jumper Configuration

For structural construction, close-riveted skin construction which divides lightning current among a large number of rivets may be considered an adequate discharge path. A minimum number of rivets and rivet size should be determined for locations where lightning current is designed to pass through structure.

Flight control surfaces and cables should be bonded to ensure that currents flowing through the control surfaces during a lightning event are passed with little or no damage to the flight control surface. In many cases it is also important to ensure that an alternate designed current path is provided around each bearing or hinge to prevent damage from high currents. Where jumpers are shielded from a direct lightning strike, exposed movable surfaces having a single hinge must be protected by a minimum number of bond jumper installations. For many designs, it may be adequate to protect single hinge moveable surfaces with a minimum of two No. 12 AWG copper jumpers (or equivalent) installed in immediate proximity to the hinge. The provision of bonding jumpers on control surfaces is an important part of the lightning protection design. As a result of this importance, these bond jumpers require the engineering evaluation presented in these case studies to ensure that there is an adequate protection over the life of the installation. Where two or more hinges are used additional design criteria may be established to address redundancy of lightning path protection. For installations that have multiple hinges, it may be determined that each hinge must be protected by a minimum of one jumper to meet these requirements. Where the jumpers that protect control surfaces protrude outside the vehicle or are otherwise exposed to a direct lightning strike, their size may be altered to carry the higher current associated with direct attachment within the lightning zone specified. In this case, bond jumpers may be increased to No. 4 AWG. In order to control the implementation of bonding jumpers within a design, a table of the different applications for bond jumpers including various lightning threats can be created to demonstrate that the appropriate protection is applied.

Electrically bond mechanical control cables at their outboard ends to prevent high potentials from appearing at the control position. It may be impractical to bond the cable directly; therefore, apply the jumper to the section or drum where the cable terminates may be the best design approach to implement the bond. The jumper should be installed to protect the bearing of the control cable pulley. If there is a possible lightning discharge path from the control surface through linkages to the cable section, then it is good design practice to electrically bond each linkage.
For tubes that carry combustibles, where lines carrying combustibles are located on the exterior of the air vehicle, bonding at extremities is necessary. Practical implementation of bonding schemes that protect combustible transport elements such as tubing may be grounded at extremities, joints, and at a specified distance between ground points when the tubing is greater than a specified length. For bonding of these types of transport elements, it may be appropriate to bond every X feet along the length of the tube if the distance between joints is greater than X feet (design requirement for distance between bonds retained).

Lightning discharge paths must also be provided at all possible points of entry into the aircraft. The discharge path must be low inductance for the short rise time initial current component, and low resistance for the longer duration DC component. As discussed in the bond jumper section of this thesis, these entry points may include locations on the aircraft such as: navigation lights, fuel filler caps, fuel gage covers, fuel vents, fuel tank access panels, antennas, and exposed connectors that penetrate from outside the aircraft to inside the aircraft.

To determine the appropriate method used to create the bonded joint, solder connections must not be used on jumpers that are required to carry lightning currents. The method of attaching terminals to jumpers must be verified by test to be satisfactory for lightning discharge. Such tests must meet the requirements of military specification MIL–B–5087 [5.27]. Since much development has occurred over many years to advance electrical bonding guidelines, MIL-B-5087 was cancelled in 1997. Though the military specification MIL-B-5087 provides general guidelines for bonding and grounding (earthing) important lightning protected locations, it is also acceptable for an aircraft design program to adopt specific internal guidelines and requirements to ensure appropriate methods are used. For the aircraft in the case studies, the OEM uses an internal requirements specification Aircraft Requirement (reference retained) to provide installation design guidance for earthing of equipment and aircraft structure [5.29]. The specification, (OEM specification number retained) and the dash numbered specifications do not violate MIL-B-5087B, MIL-STD-464 [5.30] or the U.S. National Electrical Code. However, MIL-B-5087B, MIL-STD-464 or the National Electrical Code or any other specification may not be used in lieu of the OEM specification and the dash numbered specifications, unless specifically approved by a using group. In case of a conflict between the dash numbered specifications and the engineering drawing developed by design engineers, the provisions of the engineering drawing shall prevail. The dash numbered specifications (reference retained) require certified personnel and test equipment. The dash numbered detailed specifications are listed in Table 5-17.

Specification Number*	Title
Temp-1	Electrical Bonding of Receptacles
Temp-2	MIL-T-83454/4 Preinstalled Ground Stud Installation
Temp-3	Standard Preinstalled Ground Stud Installation
Temp-4	Direct Ground Stud Installation
Temp-5	Terminal Installation on Preinstalled Ground Studs
Temp-6	Electrical Faying Surface Bonds
Temp-7	Driven Rivet Electrical Bond
Temp-8	Electrical Bonding - Ground Block Installation
Temp-9	Electrical Bonding - Static Discharger Assembly Installation
Temp-10	Electrical Bonding - Clamp Installation on Tubes/Conduit
Temp-11	Electrical Bonding - Fitting and Coupling Installations
Temp-12	Electrical Bonding - Bulkhead Fitting Installation
Temp-13	Electrical Bonding of Fasteners to Conductive Finishes on Composites
Temp-14	Electrical Bonding of Composite Panels
Temp-15	Preinstalled Ground Stud Installation in Carbon Fiber Reinforced Plastic (CFRP)
Temp-16	Dual Hole Terminal Direct Ground Stud Installation
Temp-17	Electrical Bonding of Carbon Fiber Reinforced Plastic (CFRP) Structure

Specification Number*	Title
Temp-18	Electrical Bonding Through Fastener - Clearance Fit Hole
Temp-19	Electrical Bonding Through Fasteners - Interference Fit
Temp-20	Electrical Bonding Using Sleeved Bolts
	*actual specification numbers retained

Table 5-17 OEM electrical bonding specification family tree

This bonding specification forms a part of each dash numbered specification. When no dash number is specified on the Engineering drawing, this specification applies. When specified, the dash numbered specification takes precedence over this specification. For specific bond applications that require additional protection from the effects of moisture that can cause corrosion and degrade the bond, sealant may be specified. Different sealants are available that perform differently with regard to heat resistance, elasticity and penetration protection. Sealant specifications are applied by one of three categories as shown in Table 5-18.

Category	Sealant application method
Cat A1	Not sealed
Cat A2	Fay seal – Sealed between two surfaces by application of sealant spread over the surfaces before assembly and then compressed to create an electrical bond between the surfaces.
Cat A6	Fillet seal – Sealed between two surfaces by application of sealant spread at the joint between the two surfaces.
	*actual Cat numbers retained

Table 5-18 OEM sealant category nomenclature

In cases where the application of the joint requires electrical connection but the surface is not exposed to potential moisture, a joint may be designated without sealant. These applications may be found in areas within the aircraft interior or on surfaces where excessive heat keeps the joint dry such as that found on an engine structural component underneath the engine cowling. Fay surface seals are excellent for protection an electrical bond since the sealant is compressed which creates a tight seal within the adjoining components. This fay seal type of joint may not be as easy to remove in applications where a component is expected to be replaced. Fillet seals are good for eliminating exposure to outside moisture, however, a fillet seal may also “trap” moisture if the sealant is compromised. There may also be presence of moisture in joints that are fillet sealed due to condensation between the two surfaces in the joint. If a fillet seal is compromised by a pin hole in the sealant due to improper installation or accidental damage, the fillet seal can actually draw moisture into the space between the two surfaces due to the changes in pressure outside the seal and inside the seal as the aircraft moves from one altitude to another. Selection of the appropriate sealing approach is determined by use of good engineering judgment. Application of the proposed methodology can assist with providing a more “scientific” approach to selection of the most effective joint design.

In order to apply a sealed joint properly, the surfaces of the components that are in intimate electrical contact should be cleaned. Different cleaning methods are use depending on the type of materials that are used to create the electrical connection within the joint. Table 5-19 provides an example of how requirements may be defined for cleaning surfaces in preparation for sealant.

Bond Category*	Bond Surface		Cleaning Method	
	Material	Finish	Designator	Description
A1,A2,A6	Aluminum	Anodized	CM1	Abrasive Clean
		Bare with or without grease, oil or compounds, oxide film contamination or other contaminants	CM1	Abrasive Clean
		Chemical conversion coating (corrosion protection)	CM1	Abrasive Clean
		Paint, primer, or enamel	CM1	Abrasive Clean
A1, A6	Aluminum	Chemical conversion coating (corrosion protection) with or without grease oil or compounds, oxide film contamination or other contaminants	CM3	Solvent Clean
	*actual bond category numbers retained			

Table 5-19 Cleaning Methods for aluminum electrical joints

Electrical Bonding for aircraft designs have been controlled by the requirements of MIL-B-5087, “Bonding, Electrical, and Lightning Protection, for Aerospace Systems” [5.27] on many aircraft development projects. The original issue-date of MIL-B-5087 was 1949 and addressed the “how-to” requirements. Military services with commercial manufacturing assistance have tried on several occasions to revise the bonding requirements to address new manufacturing techniques and technologies. This adds complexity to the decisions that are required when establishing requirements for aircraft design. However, the revisions just added more techniques without deleting older techniques. The latest version, Revision B, was issued in 1964 and is sometimes referred to for creation of the latest generation requirements. Electrical bonding requirements in these Military standards have not kept pace with today's understanding of electrical bonding and its effects on system performance. This situation results in the creation of design requirements that are sourced for original documents such as MIL-B-5087 with certain departures used to meet special needs or more recent understanding of optimal bonding and grounding criteria.

More recently issued guidance for the electromagnetic compatibility design for a system is governed by Interface Standard MIL-STD-464, "Electromagnetic Environmental Effects Requirements for Systems", issued March 18, 1997 [5.30]. This standard replaces, for the most part, the requirements and the techniques recommended within older documents with performance based requirements. One of the superseded documents is MIL-B-5087B [5.27].

Some designers feel that no commercial standard exists that adequately addresses the bonding considerations associated with operation in the severe electromagnetic environments of military aircraft and missiles. Contrary to this belief, many commercial aircraft designers have developed far more advanced guidance internal to specific companies. In addition, the committee's assembled under the auspices of the Society of Automotive Engineering have generated guidelines published within Aerospace Recommended Practices (ARP) that further advance the library of known design requirements in the 1990's. In many cases however, many government contracts continue to invoke MIL-STD-464, along with companion documents MIL-STD-461 and 462. For the aircraft in the case studies, this thesis contains specific guidance provided in the following paragraphs that may have been sourced originally from the military specification, the SAE, ARP and internal OEM design guides.

Many current design and manufacturing processes for electrical bonding are based on MIL-B-5087B. The use of modern materials in system structure designs, such as conductive and non-conductive composites, conductive form-in-place gasket materials, etc., is not addressed by MIL-B-5087B. When using new materials, electrical bonding requirements may be left to the manufacturer to establish and propose the techniques and quality checks that will be established for the manufacturing processes. As an aircraft manufacturer selects sub-contractors that are responsible for production of electrical bonding designs, these situations may create programmatic issues (some requiring contractual modifications) due to differences in interpretations of contract-requirements.

As a result, it is not adequate to simply reference a requirements document for implementation of a physical design. Non-consistent contractual interpretations of specifications such as MIL-B-5087B, and associated deviation/waiver exceptions, can cause the internal bonding manufacturing requirement/procedure to be different for each airplane platform design implemented. For example, some manufacturing procedures will allow electrical bonding methods on the classic aircraft designs of the 1960s that are not permitted for the aircraft in these case studies. This adds complexity to an already complex process for manufacturing multi-type, multi-customer aerospace products in a common facility. In the end, design and manufacture of the aircraft in these case studies requires close attention to specific design requirements and deviations from industry standards.

5.8.8 Bonding for the Aircraft in the Case Studies

Based on analysis done during the design of the airplane lightning zones for the aircraft in the case studies, standard requirements are defined that specify the type of protection and current handling capabilities that must be designed for each location and application.

Possible impacts of lightning to unprotected aircraft include structural damage, fuel ignition, and the generation of electrical transients. Structural or skin damage could occur as the result of lightning current flowing through structural or skin components where the path impedance could cause overheating. Fuel ignition could occur as a result of current flow through joints or fasteners exposed to fuel or fuel vapors such as in the fuel tank where poor joint contact could cause arcing or heating. Electrical transients could be generated if high lightning currents such as from nose to tail of the airplane flow in parallel with wiring and induce a transient current in that wiring. These transients can also result by induction from the magnetic or electrical fields created by nearby lightning strikes through unshielded openings or apertures. Transients can also occur if high current flow through the impedance of a path such as a ground plane results in a high voltage drop along the path which would create a ground reference voltage difference between different points on the ground plane. As discussed in this thesis, effects resulting from the transfer of lightning current to a localized location on the aircraft structure are called direct effects. Effects resulting from the induced currents caused nearby lightning current either on the airplane or nearby are called indirect effects.

Bonding and grounding provides protection from lightning damage by channeling the lightning current in a controlled alternative low resistance path to minimize impact on structure and equipment. Grounded diverters such as that on the radome and some antennas on the exterior of the airplane are designed to direct the strike away from vulnerable areas. Grounded conductive surface layers over composites such as foil or screens help dissipate the strike current and prevent skin penetration and provide a shield to reduce induced effects. Bonding (or earthing) jumpers from moveable control surfaces to fixed surfaces prevent damaging current flow through hinges and actuators. Proper use of conductive fasteners to insure low resistance joints in the skin and structure insures that sparking and heating at the joints does not occur in fuel area. The current return network provides a low resistance path from nose to tail and to the tips of the wings and empennage to channel much of the lightning current in a path alternate to the airplane skin and structure and provide a safe path for lightning current from entry to exit. Properly grounded equipment and wire shields to the aircraft ground plane reduces electrical transients.

The lightning protection scheme (Class 4 in the Table 5-16) for the airplane depends on all of the airframe components, the ground paths designed for lightning current, and structures being electrically bonded together to form a common ground plane. Current distribution analytical models and threat assessments depend on the ground path architecture. This same architecture enables the responsible design community to establish qualification levels for all systems equipment.

Diverter strips, structure, and all components and surfaces shall be electrically bonded or protected to control and divert lightning currents, and to minimize the direct and indirect effects of lightning.

Figure 5-57 illustrates how the high currents and voltages resulting from lightning strike can cause arcing.

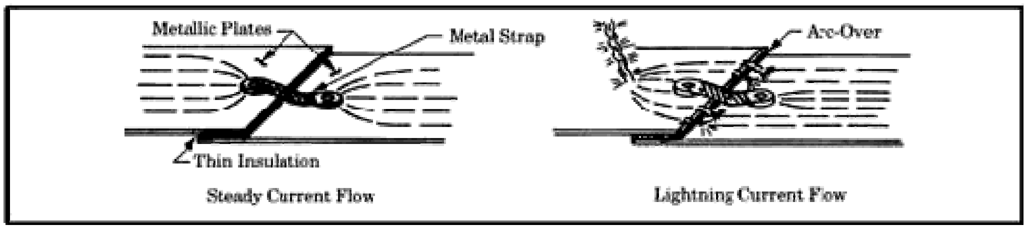


Figure 5-57 Arcing potential from lightning strike

5.9The Continued Airworthiness of Lightning Protection

Airplanes in flight are susceptible to various environmental hazards including lightning and high-intensity radiated fields (HIRF). Both of these conditions can impose sudden, serious damage to critical and essential airplane systems such as electronic engine controls, high lift devices, and primary flight controls, and can affect safety of flight. Instructions for Continued Airworthiness (ICA) ensure the availability of the inherent safety and reliability of the system function. This requirement is levied against systems whose failures can cause or contribute to a Catastrophic or Hazardous/Severe-Major failure condition. This requirement is satisfied during the design phase of the project by a release from affected Engineering Groups defining all significant protection items and documentation of the preferred and optimized design for each component installation.

Aircraft electromagnetic protection has always been focused on the design, test and analysis required for certifying aircraft. That focus is now expanding to include the continued airworthiness of electromagnetic protection over the entire life of the aircraft. A better understanding of the scope and magnitude of maintaining assurance is needed for continued electromagnetic protection and safety over the lifetime of the aircraft [5.35].

As discussed, for wiring installations that support critical and essential systems operations, protection from these conditions is built into airplanes through shielded enclosures and shielded wiring, which are grounded to airplane structure. Airplanes also operate under the constant extremes of pressure and temperature while exposed to moisture, shock, and vibration. These can degrade the built-in protection integrity of shielding systems, bonding installations and structures, requiring operators to periodically test the protection schemes unless the protection is proven within the design to last the life of the aircraft. If HIRF/Lightning protection components in the ground paths progressively lose their capacity to conduct and divert electrical current, then the associated and intended HIRF/Lightning Protection function is correspondingly impaired.

Deterioration can occur due to several operational and environmental sources. The following are some of the more common causes of deterioration that can affect lightning protection continued airworthiness.

1. Corrosion of components' conductive elements can be a major problem in this respect and is aggravated by exposure to environmental moisture and fluids. One direct consequence of corrosion is increased electrical resistance and diminished capacity to conduct the electric current arising from exposure to HIRF or lightning.
2. Designed mechanical integrity (faying surface electrical bonds, grounding terminations, connector mating, etc.) can degrade, thus increase electrical resistance between interfaces and decreasing the effectiveness of the protection function being provided for HIRF/Lightning.
3. Vibration in flight can loosen or separate connections and thereby increase electrical resistance.
4. Internal components of equipment line replaceable units may degrade or fail for various reasons, one of which may be exposure to sufficiently potent lightning-induced voltages.

Categories of lightning protection are discussed in the methodology section of this thesis. For each category of lightning protection a plan must be put into place to ensure that the protection continues to function during a lightning event over the life of the aircraft. Categories of lightning protection can be described as following:

1. **Internal Protection** - Components inside the Line Replaceable Units (LRUs) of Electrical and Electronic Systems. HIRF/Lightning protection components located inside the equipment of Electrical and Electronic Systems include diodes, capacitors, filter pins and transient absorber devices (Tranzorb). These components located inside equipment are categorized as Internal. During service, the integrity of these components typically is verified by testing the host Line Replaceable Units (LRU) according to an Acceptance Test Procedure (ATP) when they are removed from the airplane for maintenance purposes. Components within equipment can also prove continued airworthiness through mathematical means by showing the life of the component exceeds the life of the equipment.
2. **Mechanical Protection** - Mechanical Components are typically non-wiring components that are installed to protect against the adverse effects of HIRF/Lightning and may include ground straps, isolation devices, ferrite suppressors, etc. During service the integrity of these components is typically verified by testing during scheduled maintenance. In order for these components to be identified to require scheduled maintenance, the design methodology is used to show any potential unacceptable deterioration.
3. **Secondary Structural Components** - Structural Components include disconnect brackets, trays and shelves, etc. Disconnect brackets that are used to mount critical connectors at production breaks are a good example of structural

protection. During service the integrity of these components is typically verified by testing by testing during scheduled maintenance or upon removal and installation of related interfacing components.

4. **Primary Structural Components** - Structural Components include skin, walls, composite panels, ribs, spars, stringers and beams. During service the integrity of these components is typically verified by testing by testing during scheduled maintenance.

Protection components listed in this chapter are tested any time a bond path check is performed. These bond checks drive current through the mechanical, wiring, primary structure and secondary structure in order to determine appropriate impedance between these components exists. This is demonstrated in Figure 5-49 where the bond path is defined through wiring, brackets and aircraft structure.

Compliance to FAR 25.1529 [5.23], as applied to HIRF/Lightning protection components, is very much dependent on the type of component under consideration. Components associated with electrical or electronic systems are generally divided into two broad categories: 1) protection components external to line replaceable units, 2) protection component within line replaceable units. Components associated with fuel systems and structural installations are also categories of lightning protection, though there are more specific regulations written by regulatory authorities to address ignition sources due to lightning and other potential energy sources such as fault currents and static energy. The criticality of each protection feature or component is the associated criticality of the system in which the components are associated. If the LRU in Figure 5-58 is considered critical or essential equipment, then all components within the bond path are considered with the same level of importance to the continued airworthiness of the system.

In Figure 5-58 the bond path associated with lightning protection is from the loom shield to the backshell to the bracket and then to structure. Continuing from the backshell the ground path for the lightning might also take the path of backshell to receptacle on the bracket to the connector plug on the other side of the bracket, through the shields in the loom and to the next connector backshell on another bracket. In the case of an LRU installation, the bond path in Figure 5-58 is through the shields in the loom to the backshell on the aircraft loom then to the plug, through the receptacle and into the LRU case. The LRU case may be electrically bonded to the aircraft structure through a fay surface bond between the LRU and the structure on which it is mounted. If an LRU cannot achieve an adequate bond through the interface of the LRU case and the aircraft structure, then a bond strap or “earthing wire” may be mounted to the LRU case and the airplane structure to achieve the required electrical bond.

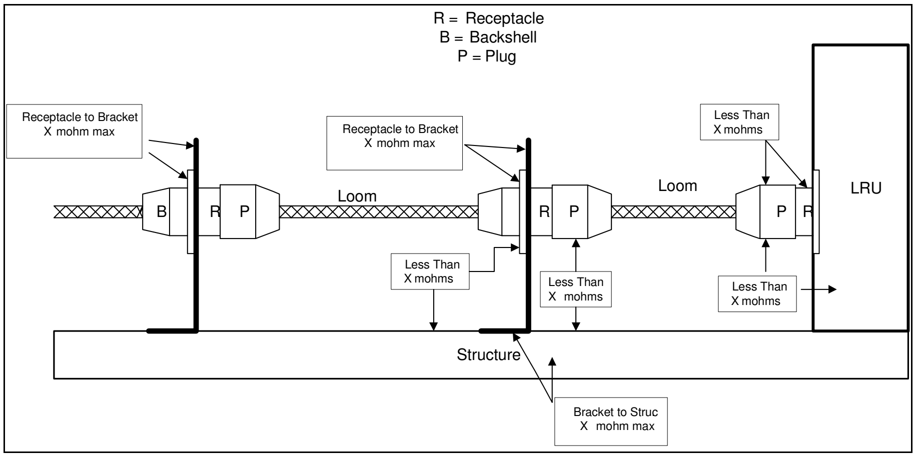


Figure 5-58 Bond path from equipment and connectors to aircraft structure

Electrical, electronic, and fuel systems installed on commercial airplanes are protected by various means against adverse effects caused by exposure to High Intensity Radiated Fields (HIRF) and lightning. These HIRF/Lightning Protection Systems are comprised of components that avoid, eliminate, or reduce the consequences of a HIRF or lightning event. The means of protection are the airplane structure itself, sub-structural components, mechanical components, components of the installed wire looms and discrete components that reside within the line replaceable units of systems themselves.

The statutory requirement that applies to these various protective components in respect of assuring their Continued Airworthiness is defined in FAR 25.1529, Instructions for Continued Airworthiness [5.23]. In the design of the aircraft used in the case studies, the manufacturer has established detailed requirements that are intended to ensure compliance with FAR 25.1529 [5.23]. The requirements apply to HIRF/Lightning assurance, test plans, procedures, analytical techniques and deliverable documents and appropriate maintenance program development.

For wiring protection, adequate bond path is provided by proper shielding, electrical interface preparations between line replaceable units and aircraft structure as shown in Figure 5-58 for wiring installations. The wire looms that convey signals to Critical and Essential airplane systems can also convey current induced by exposure to lightning or HIRF that can create upset or failure during critical flight operations. The levels of induced current are reduced by incorporating electrically conductive shields within and around the wire looms. These shields therefore provide a secondary line of defense in respect of HIRF/Lightning protection. In addition, Critical and Essential airplane systems commonly possess within them passive protection components to “stand-of the effects of large voltages that can be generated at the connector interface to the equipment if not properly designed. These work by absorbing or diverting residual electric current that impinge upon the system via the connected wire looms and the external connectors. These internal components provide a third line of defense in respect of HIRF/Lightning protection [5.34].

Wire loom shielding of aircraft wiring harnesses, electrical bonding, and grounding are all used to provide electromagnetic protection in aircraft. In earlier design periods such as that represented for the aircraft used for these case studies, the effectiveness of these protection methods was assumed to be maintained using periodic detailed visual inspections and DC bond checks after any replacements or repairs. This assumption appears valid because of the low number of catastrophic occurrences involving lightning strikes. However, the continued effectiveness of electromagnetic protection methods becomes more important as the use of and complexity of the Avionics used in the aircraft increases. Continued effectiveness of the electromagnetic protection methods is also very important as the amount of composite materials used in the manufacture of the aircraft is increased.

Because of the increased importance of electromagnetic protection, the FAA along with the industry has developed measurable standards for assuring the continued effectiveness of electromagnetic protection. Developing measurable standards requires a thorough understanding of the electromagnetic environment and the necessary measurement tools. Degradation of lightning protection can result in reduction of the bond path or electrical path conductivity. In response to these reductions in conductive efficiency, one may use a loop resistance tester on certain critical wire looms to determine reduction in conductivity over time. Degradation in general is both environmental and time sensitive. Long term behavior of conductive elements are affected by factors like temperature, moisture, dynamic service loads, accidental damage, foreign object damage (FOD), and system operating fluids such as hydraulic fluid either in isolation or in association of more than one of these factors. For a required design life of 20 years or more of these materials, it is not practical to perform tests on either materials or structures for very long periods to cover the design lifetime, especially on a newly developed technology. Therefore, there is a strong need for accelerated lifetime characterization methodologies which can predict the degradation of components that protect against the adverse effects of lightning in order to assure the integrity and safety of lightning protection components. Since it is often impractical to expose lightning protection component to the multiple degradation threats over an extended period of time representing the average 20 year life goals of an aircraft, it is very much essential to understand their durability issues before they can be used with confidence in any aircraft design application. To assist with this challenge, this work proposes practical application of a methodology to converge all known elements of the protection components potential degradation modes, known patterns from service experience and leveraged use of test data that may be generated for other design evaluations.

Environmental conditions that damage airplane systems include moisture from rain and salt air, which continually bathes external wiring, connectors and other grounding installations such as bond jumpers. As an example, wide pressure swings from altitude changes, in conjunction with extremes of temperature, can force moisture into connectors and junctions. Small air cavities in connector back shells are susceptible to internal condensation even if completely sealed to outside air. Climb out from airports where temperatures reach above 100°F (38°C) to flight at 40,000 ft., where temperatures can fall below -67°F (-55°C), causes these air pockets to shrink and draw moist outside air inside. Descent from low-pressure altitudes through clouds and rain forces moist air into connector cavities when outside pressure builds at lower altitudes. This effect can occur even in pressurized areas of the airplane. Airframe vibrations and shocks from landings and turbulent flight can loosen fasteners and connectors, creating additional paths for moisture to enter.

The inevitable ingress of moisture causes corrosion which is also discussed in depth within these case studies. Corrosion degrades electrical ground paths through a chemical interaction between metal and another element, usually air (oxygen), water, salt, or chemicals such as hydraulic fluid. The shield grounding techniques used on airplanes involve metal-to-metal contact at junctions. The presence of oxygen or water causes an oxide to form between the contacting surfaces. The oxide is an insulator, which limits the flow of electrical current. Gradually the resistance across the junction increases and, over time, the electrical junction can be completely broken. Degradation of this type results in a higher resistance path to ground, which allows greater coupling of lightning or RF currents to internal wiring. This degradation is not evident to maintenance personnel, and extreme instances of corrosion or loosening of connectors can cause the effectiveness of the lightning protection to diminish unacceptably.

The continued airworthiness of the different lightning protection designs relies heavily on the location of the equipment and wiring, use of effective wiring, use of good grounding or earthing practices, and building equipment to withstand transients as well as long term environmental effects. All these tactics must be incorporated into the aircraft design and the installed equipment. As an example, a new shielded cable properly installed will exhibit a certain amount of resistance in the shield circuit. By monitoring this resistance, maintenance personnel can determine the ability of the shield to protect internal wiring. Any increase in resistance indicates that a problem is occurring in the circuit, such as corrosion at a junction or loose hardware. When the resistance reaches a certain level, maintenance personnel must take corrective action, usually by cleaning the affected junctions, securing loose connections, or replacing the cable. The concept of this research is to eliminate the need for maintenance by ensuring that the proper design steps are taken during the design phase of the aircraft development. This is accomplished using the methodology and is put into practice by use of analysis sheets included in the case studies. One consideration for the outcome of the assessment in the methodology can be replacement of a different component or relocation of the component to reduce potential degradation.

In 2004 the US Department of Transportation sponsored a study to investigate the continued airworthiness of aircraft wiring [5.36]. This report presents the results of the effects of aircraft wiring harness shield degradation when harnesses and connectors are subjected to a variety of environmental, mechanical, and vibration test conditions adapted from RTCA/DO-160-D. Two aircraft manufacturers each fabricated six identical test panels. Each panel had two 24″ shielded wire looms with back shells and cable end connectors attached to separate termination boxes and center bulkhead brackets that were mechanically mounted and electrically bonded to the ground plane test panel.

One panel served as the baseline, and the other five panels were exposed to three severity levels for each test. Direct current bond (joint) resistance, shield loop resistance at 200 Hz, and network analyzer swept-frequency impedance measurements from 10 Hz to 10 MHz were taken of each panel before and after each test to record the electrical changes. Careful visual inspections and digital photographs were taken to record the visual changes.

Comparisons were made in detecting shield degradation using loop resistance measurement techniques, swept-frequency impedance measurements, and visual inspection to identify unsafe conditions. The wire loom shield loop resistance subjected to degradation increased from 9.7 to 16.3 milliohms, or less than 5 dB. Little change in wire loom inductance was observed, except at high levels during the mechanical shield degradation tests. It was found that the shield degradation increases the resistance of the shield loop much more than its inductance, providing evidence that loop resistance measurements are adequate to detect shield degradation without taking swept-frequency impedance measurements.

This work revealed that visual inspection can pinpoint the source of shield degradation before a significant increase in electrical shield loop resistance is measurable. However, visual inspection is only possible if the wiring harness and connectors are visually accessible on the aircraft. Otherwise, loop resistance measurements on any accessible part of the harness, performed by a trained and skilled operator, can detect shield degradation but cannot necessarily pinpoint the location or source of the problem without further joint resistance measurements.

Though the results of this test case reflect a small sample of wire harnesses with degradation caused by salt spray, vibration, mechanical degradation and in some cases a combination of test threats, data gathered on the aircraft in the case studies suggests that some degradation is much higher than the 5 dB suggested in this report. As part of this research and development it was discovered that the tests performed in the reference [5.36] test report are not consistent with known degradation experience over time on the aircraft used in the case studies. The following is a summary of results observed for each test type:

Temperature and Altitude Test: This test was performed to evaluate the level of degradation on aircraft wiring harness shield characteristics when exposed to various temperature and pressure extremes that are usually associated with altitude change during normal flight operations. The test panels were exposed to low, medium, and high levels of variable temperature and pressure conditions in the environmental chamber. Visual inspection, loop resistance, and dc resistance measurements were recorded initially and after each exposure level. Test panels showed no considerable variation in the loop impedance values between the initial and final readings. A gradual increase in the resistance values was noticed as the severity level changed from low to high, but the increase was within tolerance limits.

Neither of the test panels showed signs of visual degradation at any level of temperature and altitude testing.

Salt Spray and Humidity Test: Test panels were exposed to low, medium, and high levels of a corrosive environment in a salt spray chamber. A visual inspection and loop and dc resistance measurements were recorded initially and after each exposure level. Exposure levels were varied from about 30 hours at the low end to about 200 hours on the high end (actual exposure times retained). No noticeable corrosion was seen on the low spray exposure level. For the medium exposure, a visible film was seen on the connectors. Corrosion is clearly visible on the high spray exposure level on the shield termination screws and on the screws joining the bulkhead to the ground plane test panel. A gradual increase in the resistance values was noticed as the severity level changed from low to high, but the increase was within standard tolerances established by the test agent. Test panels were found to be visually degraded at the low-level test and became heavily corroded at the end of the high-level test. Total loop impedance levels rose from a baseline of approximately X milliohms for the baseline to Y milliohms at low exposure and Z milliohms at medium exposure and finally ZZ milliohms at high salt spray and humidity exposure. These values are increased as spray tests exposures are increased. Conclusions of this test determined that the degradation was not greater than 5 to 6 dB and that the corrosion which was determined to cause the increase in the loop resistance value was evident with a visual inspection.

Vibration Test: The vibration test was performed on the test panels to simulate the vibration conditions in an aircraft. Referencing the vibration curve contained in RTCS/DO-160D guidelines, the most sever vibration curve was used for the test. Due to the small size of the vibration table used in this test, the test was performed on a portion of the test panel using special designed fixtures. Vibration was imposed on the test specimen in three axes at three different levels from low to medium to high. Results of this test showed no loosening of connectors or screws. Moreover, no other visual variations were observed at any level of testing. Variations in shield loop resistance and dc measurements were within the set tolerances however there was a noticed crack in the connectors used on one of the test samples.

Mechanical Degradation Test: This test studied the effects of mechanical degradation on wire shielding. The types of degradation performed on the test panels were stretching, loosening and cutting the shield braids. These tests were typical examples of possible damage to wire looms in aircraft. For each severity level, the degradation was performed on all the shield braids on each side of the center connector, and also on the shield braids terminating at each end connector. Degradation was injected by cutting shields from a low level to a higher level. At the low level, two of six shields were disconnected. For the medium level test, four of the six wire shields were severed. And for the high mechanical damage scenario, all shields were cut. Mechanical degradation affected the shield impedance more than any other environmental test. Shield loop impedance and dc measurements were within the manufacturer’s tolerance limits at all degradation levels.

Combined Degradation Test*:* A final test was performed by applying the degradations listed above to the same wire loom starting with vibration, then temperature, salt spray, and finally the mechanical degradation was applied. The final measurements at the end of combined tests showed the overall effects of the worst possible environmental and mechanical degradation. A gradual increase in the resistance was noticed for one of the two test panels after each degradation test. The other test panel showed no noticeable increase after the temperature and altitude test. However, abnormal results were observed during the vibration tests. The loop resistance value became unstable during the salt spray and humidity test. Therefore, the mechanical degradation test was not performed. Further investigation revealed that the vibration tests internally damaged the connectors. The variations in the loop resistance for the combined tests were determined to be within the acceptable limits after all the degradation tests. Mechanical degradation was more sever on the resultant loop resistance as noticed in previous mechanical degradations tests. The test reported that no significant change was measured in bonding, grounding, and connection resistances after all the degradation tests.

Overall observations from this testing resulted in the following findings as determined by the principle investigator [5.36]:

- The temperature and altitude tests had no effect on the physical or visual characteristics of shielding for either test panels type A or B. The loop resistance for test panel A increased by 4 milliohms from the baseline to the high-level degradation test, and for test panel B, it increased by Z milliohms.
- The Salt spray and humidity testing corroded the ground plane, center bulkhead, screws, and exposed shield braids for both test panels. A slight increase was observed in the shield resistance (less than 2 milliohms) after the high-level tests of each test panel.
- Vibration testing did not vary the visual characteristics for both types of test panels. The shield loop resistance did not significantly increase at any level of degradation for test panel A. However, the connector backshells were broken during the testing for test panel type B and the resistance of the shielding went to open circuit. Test panel type B was more susceptible to vibration testing due to the size of the connector backshells.
- Mechanical degradation testing affected the physical and visual characteristics of shielding for both types of the test panels. The loop resistance increased from baseline to high level of testing by X milliohms for test panel A, and for test panel B, it increased by ZZZ milliohms.
- Combination testing affected the physical and visual characteristics for both types of test panels. The loop resistance value increased slightly from baseline to high level of testing by Y milliohms for test panel A, and it went to open circuit for test panel B because the connectors were internally damaged during the vibration testing.
- Physical degradation of shielded wire harnesses was visually observed before or at the same time of any significant loop resistance increase. Hence, it is recommended that visual and physical inspection be made the primary means for detecting shield degradation and shields should be repaired when degradation is observed. However, loop resistance measurements are advantageous when used to indicate shield degradation of those wire harnesses that are not easily accessible for visual inspection, provided the measurements are performed by trained and skilled operators.

- A further mechanical study appears warranted to investigate the shield degradation effects of fully broken and floating grounding wires on various shield configurations. That proposed study should involve loop resistance, swept-frequency impedance, and shield effectiveness measurements to compile the proper maintenance procedures.

Commentary on test results: The tests performed in the reference report [36] are one view of test data that should be evaluated against individual OEM experience. Individual OEM tests on the aircraft in these case studies performed on aircraft that are in service with 10 or more years of aging showed some different results that those in the US DOT Study Final Report, "Aircraft Wiring Harness Shield Degradation Study", August 2004 by J.B. O'Loughlin and S.R. Skinner from the National Institute for Aviation Research Wichita State University [36]. In that case, the findings of the simulations performed as part of the research results from the referenced DOT study [36] will not be used to determine appropriate design criteria as proposed in this body of work. Use of the results of this test report should be used with caution. The inconclusive nature of these tests underlines the position made elsewhere in this work that qualification tests (often requiring 500 hours or less of salt spray testing) cannot adequately represent performance of protection components installed on an aircraft years after the aircraft was produced. This also emphasizes the importance of the proposed methodology which brings requirements for continued airworthiness into the design process. Consideration of test results, including engineering and qualifications tests, are included in the assessment sheets but are not expected to be the sole basis for determining the performance of lightning protection components.

Airplane designers should preferably base their techniques for protection designs on the assumption that presence of moisture is inevitable and that the use of corrosion-resistant materials and sealants may be an excellent design alternative. However, use of corrosion-resistant materials may involve several compromises. An example is corrosion-resistant stainless steel (CRES), which is heavy and does not conduct electric current easily. Also, CRES is only corrosion resistant and not corrosion proof. Consequently, connectors are made of lighter materials such as aluminum, which is a good conductor of electricity. Titanium is also a material that has superior qualities in some respects. Though titanium is light and high in tensile strength, it also has a lower conductivity than aluminum or copper. These characteristics of titanium need to be balanced against the alternative material such as CRES which is much heavier than titanium or aluminum. Because aluminum corrodes quickly in salt air, it is usually plated with nickel and cadmium for additional protection. However, time and exposure eventually may cause materials to corrode given the right environmental threats and metals involved. The possibility of corrosion within a critical lightning protection design is the reason that regulators have mandated specific maintenance actions on certain airplane models for monitoring exposed shield paths to keep them functioning over the life of the airplane. This conclusion can be augmented with a proper design assessment tool such as the methodology proposed by the body of work associated with this thesis.

5.9.1 Certification of Lightning Protection Designs

Lightning designs are certified for application on an aircraft through assessment of design changes from past designs. In this process an aircraft designer determines designs that will require a rigorous evaluation and be declared as "new" for type certification. In the route to certification, testing may be required for new designs or testing may refer to past tests of similar lightning protection on other aircraft types. This approach allows aircraft designers to submit certification plans to the regulatory authority in an efficient and productive manner. In order to create a structure from which a regulatory agency authority can evaluate aircraft type designs, an aircraft designer might create a summary document listing all items that have been new or significantly modified from those same designs on other aircraft that have been already included in other aircraft type certifications.

For the aircraft in the cases studies, systems and structures that have been modified from earlier aircraft designs or considered a "New" design, were summarized for the certifying aviation authority. This summary contains a list of the systems and structures that have been identified as new or significantly modified for the family of airplanes represented in the case studies, or that have been significantly affected by a change to regulations or the original certification basis. These systems and structures are notable with respect to an asterisk note used in the Type Certification Data Sheets which identify those FAR/JAR 25 paragraphs (25.571. 25.607, 25.631, 25.699, 27.783(f), 25.1309 and 25.1419(c)) for which the OEM proposed showing compliance with an amendment level earlier than Amendment 25-77 for aircraft under study. For those paragraphs, the intent is to certify those portions of the airplane not new, significantly modified, or significantly affected by the change to the amendment level of previously certified airplanes. For systems with similar installations, the system may be certified by test or suitable service history.

The principal use of supplying a certification document is to establish and record a position on those systems that the OEM feels are new, significantly modified, or significantly affected by change. Although a qualitative and quantitative assessment (for catastrophic and hazardous failure conditions) will be performed on each system listed, a new Functional Hazard Assessment and System Safety Assessment (as defined in the SAE Aerospace Recommended Practice ARP 4761, "Guidelines and Methods for conducting the Safety Assessment Process on Civil Airborne Systems and Equipment", Appendices A and C, respectively) will not necessarily be conducted [5.22]. The SAE ARP 4761 document describes guidelines and methods of performing the safety assessment for certification of civil aircraft. It is primarily associated with showing compliance with FAR/JAR 25.1309. The methods outlined identify a systematic means to show compliance. A subset of this material may be applicable to non-25.1309 equipment. The concept of Aircraft Level Safety Assessment is introduced and the tools to accomplish this task are outlined. The overall aircraft operating environment is considered. The FAA has provided a memorandum [5.24] to clarify Federal Aviation Administration (FAA) Transport Airplane Directorate (TAD) certification policy on determination of system development assurance levels, hardware design assurance levels, and software levels.

When the aircraft in the case studies was certified, certain systems safety assessments were conducted that determined system criticality levels. In order to show compliance to FAR 25.1309, analysis was conducted to properly categorize systems functions and associated equipment. It is important to understand that for lightning protection, the results of FAR 25.1309 analysis is used to determine the criticality of associated lightning protection. In order to determine qualification requirements for equipment where operation of the equipment can have a potentially adverse effect on system safety, the OEM created a certification document to provide information on electrical/electronic systems equipment having a possible "catastrophic", or "hazardous/major" failure mode due to lightning [5.37]. This document contains a list of equipment associated with possible catastrophic or hazardous/major failure modes but not necessarily a list of lightning protection components. As part of this work, it is suggested that a complete list of protection components is created that protect these systems and associated functions as noted in the case studies. The table in Appendix C and Appendix D of this thesis contained in the OEM certification document, "Aircraft HIRF/Lightning System and Equipment Qualification List" [5.37], lists electrical/electronic systems comprised of equipment with functions which have possible hazardous or major failure mode(s) due to HIRF/Lightning. Equipment that maintain hazardous or major failure modes are associated with the "essential", category 4 definition per D6-16050-4, Rev A [5.33]. For the aircraft in the studies, design processes adopted to determine the certification impact of systems and equipment criticality utilized previously certified determinations to address requirements for this derivative certification program.

5.9.2 Safety Assessments and Determining the Certification Basis

The methods outlined in SAE ARP4761 [5.22] identify a systematic means, but not the only means, to show compliance. The concept of Aircraft Level Safety Assessment is introduced in ARP4761 and the tools to accomplish the task of proper categorizations and certification compliance is outlined by in ARP4761. The overall aircraft operating environment is considered during the exercise to apply proper categorization of equipment. When aircraft derivatives or system changes are certified the processes are usually applicable only to the new designs or to existing designs that are affected by the changes. In the case of the implementation of existing designs in a new derivation aircraft design, alternate means such as service experience may be used to show compliance. This technique was used extensively in the certification of the aircraft equipment contained in the case studies. The OEM Document (reference retained) titled, "Aircraft HIRF/Lightning System and Equipment Qualification List" [5.37] provides the results of the systems analysis. For the lightning and HIRF protection design methodology proposed within this work, these determinations would be important to defining the systems that require further continued airworthiness evaluation as demonstrated in the assessment sheets examples contained in the thesis.

The SAE ARRP4761 presents guidelines for conducting an industry accepted safety assessment consisting of Functional Hazard Assessment (FHA), Preliminary System Safety Assessment (PSSA), and System Safety Assessment (SSA). The ARP also presents information on the safety analysis methods needed to conduct the safety assessment. These methods include the Fault Tree Analysis (FTA), Dependence Diagram (DD), Markov Analysis (MA), Failure Modes and Effects Analysis (FMEA), Failure Modes and Effects Summary (FMES) and Common Cause Analysis (CCA). CCA is composed of Zonal Safety Analysis (ZSA), Particular Risks Analysis (PRA), and Common Mode Analysis (CMA). The process for categorization of systems failures and the impacts to components that supply functions to support these important system operations is a very complicated process and one that is determined through key strategic agreements with the regulating authorities during the aircraft design process. As such, the outcome of efforts to identify the most critical components within a lightning protection scheme is not necessary predicable.

Individual users of the guidance presented in the APR4761 include: airframe manufacturers, system integrators, equipment suppliers and certification authorities who are involved with the safety assessment of civil aircraft and associated systems and equipment. The guidelines and methods are intended to be used in conjunction with other applicable guidance materials, including ARP4754 [5.26], RTCNDO-178, RTCA Document DO-160, and with the advisory material associated with FAR/JAR 25.1309. (For engines and propeller applications, reference the applicable FAR/JAR advisory material.) The intent of the ARP4761 document is to identify typical activities, methods, and documentation that may be used in the performance of safety assessments for civil aircraft and their associated systems and equipment. The specific application of such activities needs to be established by the organization conducting the assessment and the appropriate recipient.

The APR4761 also provides general guidance in evaluating the safety aspects of a design. The primary analytical methods and tools and the relationships of these are introduced in the ARP to provide guidance also utilized by lightning protection designers. Appendices in ARP4761 provide information on: Functional Hazard Assessment (FHA), Preliminary System Safety Assessment (PSSA), System Safety Assessment (SSA), Fault Tree Analysis (FTA), Dependence Diagram (DD), Markov Analysis (MA), Failure Modes and Effects Analysis (FMEA), Failure Modes and Effects Summary (FMES), Zonal Safety Analysis (ZSA), Particular Risks Analysis (PRA) and Common Modes Analysis (CMA). Appendix L in the ARP4761 provides an example of the safety assessment process for a hypothetical system.

As discussed previously, the certification of aircraft systems may generate unique results though the guidelines may be constant. This is due to interpretations made by the manufacturer that is applying for aviation regulatory approval and associated agreements on the adequacy of the interpretations. The example in ARP4761 illustrates the relationships between the processes and methods in creating the overall safety evaluation of an aircraft or system as it develops through the design cycle. Examples presented in this ARP4761 document, including documentation examples, are intended only as guidance. Though examples are contained in the ARP4761, the examples should not be interpreted as an addition to or an amplification of any requirement. Reference is made to using the Fault Tree Analyses in this document however, for the aircraft in the case studies, an interpretation of the applicability of requirements and appropriate use of Fault Tree Analysis was determined at the time of certification and development. It should be understood that Dependence Diagrams or Markov Analyses may be selected to accomplish the same purpose, depending on the circumstances and the types of data desired. Recent developments for certification of equipment use a Markov Analysis to prove equipment internal protection is adequate for the life of the aircraft.

Failure analysis and design validation and verification have traditionally been accomplished with extensive tests conducted on the system and its components, direct inspection, and other direct verification methods capable of correctly characterizing the operations of the system. The aircraft used in the case studies was developed with much more simplified methods for system criticality and certification levels identification. These direct techniques are still appropriate for simple systems which perform a limited number of functions and which are not highly integrated with other aircraft systems. For complex or integrated systems, adequate testing may either be impossible because all of the system states cannot be determined or it may be impractical due to the large number of tests which must be accomplished.

5.9.3 Elements of a Safety Assessment

The safety assessment process includes requirements generation and verification which supports the aircraft development activities [5.22]. For all aircraft development programs there is a coordinated process for safety analyses and determinations. This safety assessment process provides a methodology to evaluate aircraft functions and the design of systems performing these functions to determine that the associated hazards have been properly addressed and related systems can prove compliance to associated regulations. The safety assessment process is qualitative and can be quantitative. These alternative approaches to safety assessments are found by the tables generated in the aircraft development program document addressing L/HIRF criticality levels [5.37].

The safety assessment process for the aircraft development program was planned and managed to provide the necessary assurance that all relevant failure conditions have been identified and that all significant combinations of failures which could cause those failure conditions have been considered. The safety assessment process for integrated systems should take into account any additional complexities and interdependencies which arise due to integration. In all cases involving integrated systems, the safety assessment process is of fundamental importance in establishing appropriate safety objectives for the system and determining that the implementation satisfies these objectives. This design methodology is maintained by constant review of design implementations and system failure conditions.

The aircraft design development process is iterative in nature as demonstrated earlier in this chapter. As a result, the list of critical and essential components contained within lightning protection designs can fluctuate throughout the aircraft design process. The safety assessment process is an inherent part of the aircraft development and can be quite varied as the design matures. The safety assessment process begins with the concept design and derives the safety requirements. As the design evolves, changes are made and the modified design must be reassessed. This reassessment may create new derived design requirements and also new design approaches that would require reassessment using the assessment sheets proposed in this work. These new requirements may necessitate further design changes in an iterative manner until all requirements are met. The safety assessment process ends with the verification that the design meets the safety requirements.

5.9.4 Types of Safety Assessments and Applications

For a broad understanding of the different known safety analysis processes, the following brief descriptions relay basic information associated with several known safety analysis approaches.

A Functional Hazard Assessment (FHA) is conducted at the beginning of the aircraft system development cycle. It should identify and classify the failure condition(s) associated with the aircraft functions and combinations of aircraft functions. These failure condition classifications establish the safety objectives. The aircraft level FHA is a high level, qualitative assessment of the basic functions of the aircraft as defined at the beginning of aircraft development. An aircraft level FHA should identify and classify the failure conditions associated with the aircraft level functions. However, if separate systems use similar architectures or identical complex components and introduce additional aircraft level failure conditions involving multiple functions, then the FHA should be modified to identify and classify these new failure conditions. The classification of these failure conditions establishes the safety requirements that an aircraft must meet. The goal in conducting this FHA is to clearly identify each failure condition along with the rationale for its severity classification. The system level FHA is also a qualitative assessment which is iterative in nature and becomes failures that affect an aircraft function. Assessment of any particular hardware or software item is not the goal of the system level FHA. If separate systems use similar architectures or identical complex components and introduce additional system level failure conditions involving integrated multiple functions, the FHA should be modified to identify and classify these new failure conditions.

The Development Assurance Level (DAL) of an aircraft function depends on the severity of the effects of failures or development errors of that function on the aircraft, crew, or occupants. The Development Assurance Level of each item depends on both the system architecture and the resulting failure effects of the item on the functions performed by the system.

A Failure Mode and Effects Analysis (FMEA) is a systematic, methodical analysis performed to identify and document all identifiable failure modes at a prescribed level and to specify the resultant effect of the failure mode at various levels of assembly. The FMEA is an analytical technique to determine the effect of a low level failure in hardware or software on the operation of a hardware item or system. The FMEA can establish that no single failure or malfunction, or combinations of failures within a system will jeopardize the safe operation of the airplane. To complete a FMEA one must generally provide for assumptions and conditions under which the system operates and is maintained. Specific faults may be defined for the system as well as how the fault becomes evident. Mechanical and electrical/electronic components that perform functions associated with the system operations under evaluations are usually also listed as part of the FMEA exercise. Common mode failures such any single failure or probable combinations of failures that can affect the system operation are be considered, to ensure that the requirement for continued safe flight can be met.

A Fault Tree Analysis (FTA) is a probability technique using failures as top level events and lower level failures within a tree relationship. The tree relationship found in the FTA is used to determine contributing factors. The FTA can be applied to determine which single or combinations of failures can exist at the lower levels that might cause each failure condition. The completed FTA facilitates technical and management assessments as it identifies only the failure events which could individually or collectively lead to the occurrence of the undesired top event. In contrast, an FMEA lists only single failures, including some which may be of no concern.

A Common Cause Analysis (CCA) provides the tools to verify independence, or to identify specific dependencies. Often discussions occur around the effects of a lightning strike event in combination with a common cause failure such as loss of multiple lightning shields due to moisture imposed across several separate channels that cause a presence of degradation equally across each channel. In particular, the CCA identifies failure modes or external events which can lead to a catastrophic or hazardous/severe-major condition. Such common cause events must be precluded for catastrophic failure conditions and must be within the assigned probability for hazardous/severe-major failure conditions. From FAR 25.1309 we see that the safety analysis must give special attention to analyzing common-cause faults.

Particular Risk Analysis (PRA) also plays a role in determination of the significance of lightning strike protection. Particular risks are defined as those events or influences which are outside the system(s) and item(s) concerned, but which may violate failure independence claims. Some of the example risks shown require analysis due to airworthiness regulations, while others arise from known external threats to the aircraft or systems. Typical risks include, but are not limited to the following.

- Fire
- High Energy Devices
- Leaking Fluids
- Hail, Ice, Snow
- Bird Strike
- Tread Separation from Tire
- Wheel Rim Release
- **Lightning**
- **High Intensity Radiated Fields**
- Flailing Shafts

The objective of the PRA is to ensure any safety related effects are either eliminated or the risk is shown to be acceptable. Having identified the appropriate risks with respect to the design under consideration, each risk should be the subject of a study to examine and document the simultaneous or cascading effect(s) of each risk [5.22].

5.9.5 Certifying a Derivative Design Aircraft

The aircraft type assessed in the case studies is certified as a "Derivative Aircraft" to a previously designed aircraft model. When aircraft derivative designs or system changes are certified, the processes described herein are usually applicable only to the new designs or to existing designs that are affected by the changes. In the case of the implementation of existing designs, a new derivation of an already certified derivative aircraft, alternate means such as service experience may be used to show compliance. Because the aircraft in these studies is a derivative aircraft of the earlier era aircraft, most of the components of the aircraft have been previously certified for direct lightning attachments. The OEM has re-certified existing components with similar installations by test or suitable service history justification. Any new or significantly modified component will use test and or analysis for verification

Failure analysis and design validation and verification have traditionally been accomplished with extensive tests conducted on the system and its components, direct inspection, and other direct verification methods capable of correctly characterizing the operations of the system. These direct techniques are still appropriate for simple systems which perform a limited number of functions and which are not highly integrated with other aircraft systems. For more complex or integrated systems, adequate testing may either be impossible because all of the system states cannot be determined or it may be impractical due to the large number of tests which must be accomplished.
The integration between hardware criticality determination processes and the software contained within certain hardware has created the need for clear guidance on criticality determinations. Guidelines for the development of airborne systems, software, and electronic hardware components, are contained in SAE ARP4754, RTCA DO-178B, and RTCA DO-254, respectively. Because these documents were not developed simultaneously, they contain different guidance and terminology. For ease and readability, the Development Assurance Level (DAL), Design Assurance Level (DAL), and Software Level (SL) are used synonymously.

A significant difference between the SAE ARP4754 and RTCA DO-178B is the guidance provided on the use of system architecture for determining the appropriate DALs for hardware and software. The FAA recognizes that consideration of system architecture for the purpose of establishing DALs is appropriate. A seamless transition between these guidelines has not been clearly established to guide the determination of system, software, and hardware DALs. Until such time, the policy below provides a standardized approach to the use and application of these guidelines and industry practices.

1. As the development assurance level determination is inherently a key process step in airplane and system safety assessment, the Aircraft Certification Office (ACO) Aviation Safety Engineer (ASE) (or authorized designee) should confirm that the airplane level functional hazard assessment (FHA), the system level FHA, and the preliminary system safety assessment (PSSA) are correctly performed

(effects of loss of function as well as malfunction should be evaluated), and that the PSSA contains proposals for DALs for the system and each of its software and hardware items. Applicants should submit these safety assessments to the FAA for approval early in the program in order to minimize certification risks.

2. System, hardware, and software DALs may be assigned based on a direct relationship to the worst-case failure condition; namely, Catastrophic corresponds to Level A, Hazardous/Severe-Major to Level B, Major to Level C, Minor to Level D, and No Safety Effect to Level E. This method, particularly when applied to system architecture with redundant elements, may result in a more conservative assignment of the DALs to the redundant elements than is necessary to comply with FAR 25.1301 and FAR 25.1309. However, any reduction in DAL from the levels determined by this method should be presented, with justification, to the ACO ASE early in the program for approval.
3. If a design contains common mode design errors that could be catastrophic, the applicable software and hardware should be assigned Level A. The software and hardware DALs could be reduced as justified by the safety assessment if the system architecture is revised to mitigate the potential catastrophic condition.
4. The guidance of SAE ARP4754 may be used to assign DALs for a system and its hardware and software components. When application of this guidance leads to assignments of DALs lower than those determined using the direct assignment of policy 2 above, the applicant should obtain concurrence of the cognizant FAA ACO with the results of the proposed PSSA as early as possible in the program in order to minimize certification risks. If the criteria of the SAE ARP4754 are not satisfied, the DALs may need to be assigned a higher level using the direct assignments of policy 2 above or using the guidance of RTCA DO-178B.
5. The guidance of RTCA DO-178B has traditionally been used and may continue to be used in the PSSA, as appropriate, to determine software levels. Where apparent differences exist between RTCA DO-178B and SAE ARP4754 on software level determination, the guidance contained in Appendix D of SAE ARP4754 can be used if additional credit is requested for system architecture and justification is provided to the responsible FAA representative in the Aircraft Certification Office for concurrence.
6. For transport category airplanes, RTCA DO-254 is applicable to all electrical and electronic devices whose correct operation cannot be verified by test and/or deterministic analysis if they could cause Major, Severe Major/Hazardous, and Catastrophic failure conditions.

The general policy stated in the six guidelines above does not constitute a new regulation or create what might legally be referred to as a "binding norm". The office that implements policy should follow this policy when applicable to the specific project. Whenever an applicant's proposed method of compliance is outside this established policy, it must be coordinated with the policy issuing office, e.g., through the issue paper process or equivalent. Similarly, although this policy is not binding on the regulatory authority, if the implementing office becomes aware of reasons that an applicant's proposal that meet this policy should not be approved, the office must coordinate its response with the policy issuing office. Applicants should expect that the certificating officials will consider this information when making findings of compliance relevant to new certificate actions. Also, as with all advisory material, this policy statement identifies one means, but not the only means, of compliance.

5.9.6 Equipment Criticality for the Case Studies

The applicability of HIRF and Lightning requirements to specific equipment is determined by a functional criticality analysis process. The result of this process is the aircraft HIRF - Lightning Criticality List which is submitted to the FAA and JAA. Criticality of failure modes is determined by the engineering group responsible for each system in a safety and functional performance assessment. Final agreement on appropriate lightning certification of systems is created when the assessment is complete and the FAA has approved a HIRF Lightning criticality list for the aircraft.

The Reference Tables in Appendix C for Critical Systems and Appendix D for Essential Systems contains a list of systems on the aircraft in these case studies whose failure would cause or contribute to a failure or function that would prevent continued safe flight and landing (catastrophic effects) or whose failure would reduce the capability of the airplane or ability of the crew to cope with adverse operating conditions (hazardous - severe/major effects).

The Reference Appendix F contains a list of new or significantly modified systems. For the aircraft certification, the OEM will perform verification tests only on those systems that are new or significantly modified. Existing systems with similar installation will be re-certified by test or suitable service history justification.

5.9.7 Maintenance Program Development

In order for a design to be certified, compliance to FAR 25.1529 is required [5.23]. Development of a minimum required scheduled maintenance program provides aircraft designers compliance in part to this requirement. The method used to determine appropriate scheduled maintenance for lightning protection components is contained in the ATA MSG-3 Guidelines Document [5.38]. In order to create an effective design, this body of work proposes that a process is necessary to bridge gaps between aircraft lightning protection design development and the development of effective scheduled maintenance programs. In order to achieve the best optimized designs, one needs to consider a process by which design alternatives are measured against constraints established by compliance to Instructions for Continued Airworthiness. In order to achieve a functioning design process that interfaces effectively with other already established design disciplines while also achieving effective evaluations of airworthiness over the life of the lightning protection installed on the aircraft, one must embrace a process similar to the one proposed in this body of work that methodically evaluates designs and seeks approval for meeting the continued airworthiness requirements from all design inputs. Some of the design expertise that may offer input to this process may be:

- Wire installation design engineering
- Electromagnetic design engineering
- Earthing and electrical bonding engineering
- Maintenance engineering

- Connector design standards engineering
- Material processes applications and corrosion prevention engineering
- Structural design engineering
- Qualification test engineering
- Service design assurance engineering
- Safety engineering

For safety related lightning protection maintenance, maintenance requirements may be created through MSG-3 analysis or certification requirements. In the case where the safety analysis requires certain maintenance tasks to be completed in order to maintain the safety probabilities required from the SSA, a Certification Maintenance Requirement (CMR) may be developed by the design community and imposed on the scheduled maintenance program. Another avenue for determination of safety related maintenance is through the use of MSG-3 analysis. Airworthiness limitations may also call out specific lightning protection tasks identified as part of Certification to FAR 25.981 [5.44] and documented in the Maintenance Program Data document as an Airworthiness Limitation Item (ALI).

For the CMR task, the calculation of event probability associated with a failure condition must take into account the time during which a latent failure can persist without being detected. In many cases, the failures are detected by normal flight crew observation or during periodic power-up or self-test routines. The latent period for these failures is short. In some cases, however, the exposure time for latent failures is associated with equipment shop tests or specific aircraft maintenance tasks. In these cases the latent period can be a considerable amount of time.

Maintenance tasks and time intervals which are identified during the safety analysis processes may become Candidate Certification Maintenance Requirements (CCMR). These requirements are discussed among design engineers and reviewed to ensure that alternate design approach can eliminate the requirement for a maintenance task to uncover latent failures. Where detection is accomplished by an aircraft maintenance task, the time interval required to meet the safety objective must be transferred to the appropriate maintenance department at the manufacturer for implementation of required maintenance procedures and time intervals into the initial minimum scheduled maintenance program.

The maintenance checks associated with safety requirements compliance are designated Certification Maintenance Requirements (CMR). A CMR is a mandatory periodic task, required to maintain the safety of the aircraft, established during the design certification of the airplane as an operating limitation of the type certificate. These checks are established in accordance with AC 25-19 “Certification Maintenance Requirements” [5.25] and are not adjustable at any time during the life of the aircraft unless a revised design is proposed along with a modified safety analysis. A CMR is required to be accomplished without consideration for aircraft operator’s convenience to complete the task since the CMR establishes the certification basis of the aircraft.

It is important to note that a CMR is derived from a fundamentally different analysis process than the maintenance tasks and intervals that result from the Maintenance Steering Group (MSG-3) analysis associated with Maintenance Review Board (MRB) activities. MSG-3 analysis activity produces maintenance tasks that are performed for safety, operational or economic reasons, involving preventive maintenance tasks, which are performed before failure occurs (and are intended to prevent failures), as well as failure-finding tasks. A CMR maintenance task on the other hand, is accomplished as a failure finding task only, and exist solely to limit the exposure to otherwise hidden failures. Lightning protection components are rarely identified as a CMR in the design process. A CMR maintenance task is also designed to verify that a certain failure has or has not occurred, and does not provide any preventive maintenance function.

The MSG-3 process examines failure conditions by using the "Next Failure'' criteria. (e.g., what is the next worst thing that can happen, given the first failure has occurred?) Once the MSG-3 process is complete, the minimum maintenance required is established in the Maintenance Review Board Report document, or MRBR. Before becoming a CMR, a potential CMR, known as a Candidate CMR (CCMR), is reviewed by a Certification Maintenance Coordination Committee (CMCC), which will decide if the candidate will become a CMR. Details of this process are delineated in AC 25-19 [5.25].

Once established, a CMR task must be accomplished by the operator at the prescribed intervals, derived from the safety analysis, to maintain the airworthiness certificate of the aircraft. Where the detection method is identified to be provided by test, assurance must be provided that the test procedures in fact detect the latent failures of concern. The underlying goal of any system design safety assessment should be to generate an absolute minimum number of CMRs.

The aircraft designers determined the criticality of electrical/electronic equipment along with the rationale and/or supporting documentation for each critical and essential piece of equipment in EMC Category 4. This equipment identification is used to determine associated wiring and connectors that provide key lightning mitigation functions and may require maintenance. Using this list of equipment, the designer can begin the design evaluation required to establish an applicable and effective maintenance program. For the aircraft, documentation was usually supplied in the form of a certification plan, a system safety assessment, a FMEA, or a FHA. In a few cases where the OEM documents were not generated for certification plans, the appropriate FAA letters were referenced to identify appropriate accounting for the equipment in these categories. Also, equipment tested to critical levels are referenced to the aircraft System Safety Assessment document (reference retained) where appropriate to prove compliance to the certification requirements.

All critical functions causing catastrophic failure modes due to HIRF or Lightning have been identified by this list and by the document (reference number retained). Since it was not within the scope of (reference number retained), to capture all essential functions (and associated hazardous/major failure modes), the method used to capture essential functions in this list was an ATA sort of all equipment. The "Rationale and/or Supporting Documentation" information was not acquired for nonessential and electromechanical equipment since HIRF and Lightning compliance is not necessary for this equipment (note general phrases "Non-Essential (or Minor) Equipment Classification" and "Electromechanical Device”.

As the aircraft design is created and equipment designs details are determined, the use of the methodology may assist with avoiding unnecessary maintenance through application of a detailed continued airworthiness evaluation. Key to this evaluation is the identification of the components, systems, and degradation modes. More will be discussed in the conclusions section of this thesis regarding the integration of the design methodology and the maintenance program development methodology contained in the MSG-3 document.

Maintenance Program Development Source Data

HIRF/Lightning requirements have been applied to various certification programs for at least 10 years. At the onset of application of these requirements, the terminology used was not HIRF, but rather “Protection from RF Fields.” The early issue papers and special conditions evolved from RF Fields to High Energy Fields (HERF) to what we have today, High Intensity Radiated Fields or HIRF. This caused the regulators within the industry to develop special conditions to address HIRF issues not adequately addressed by formal regulations. These issue papers were provided to aircraft manufacturers in the form of “special conditions” written in letter format to clearly provide guidance in the absence of FAR/JAR or Advisory Circulars. Lightning protection requirements took a parallel path of evolution, with those requirements also changing along the way.

Today, for transport airplanes, the lightning certification falls under FARs 25.581 (structure protection) [5.42], 25.954 (fuel system protection) [5.43], 25.981 (ignition prevention - also SFAR 88 for aircraft certified prior to ratification of 25.981) [5.44], and 25.1316 (electrical and electronic system protection). Since the HIRF rule was not in place until 2007, HIRF certification continued to be based on special conditions. Prior to approval of FAR 25.1317 (HIRF protection requirements) [5.56], FAA notice N8110.71 spelled out the interim policy that FAA used as the basis for the special conditions. Under FAR 25.1316 [5.54] (electrical and electronic system lightning protection) critical and essential systems (Level A and B) must be protected and certified. Under the HIRF special conditions and now the FAR 25.1317 [5.56], only critical (Level A) electronic systems must be protected and certified.

Continued airworthiness of HIRF and lightning protection falls under FAR 25.1529, Instructions for Continued Airworthiness [5.23]. Advisory circular AC 20-136 gives acceptable means of compliance for electronic system lightning protection. Within this AC, Section 7 provides guidance on maintenance of lightning protection components and systems. This section states that lightning protection maintenance actions should be identified, and may include periodic inspections and tests. Section 7 recommends engineering evaluation and validation of these maintenance actions.

The FAA interim HIRF policy N8110.71 also contains similar guidance for the maintenance of critical system HIRF protection.

In the late 1990's the FAA agreed with the need for a HIRF and lightning maintenance program to be developed. At that time, instructions for the development of a HIRF protection maintenance program was not included in the MSG-3 analysis guidelines. As a result of this shortcoming in regulations and maintenance program development guidelines, regulators created an Airworthiness Directive (AD) related to the HIRF and lightning protection on several aircraft types. The OEM aircraft (aircraft reference retained) is the first aircraft design to be subjected to the requirement to develop a HIRF/lightning protection maintenance program. The FAA AD resulted from data gathered during the OEM engineering validation of the aircraft HIRF/lightning maintenance programs. The AD has illustrated the need for maintenance actions for HIRF and lightning protection.

Since the aircraft mentioned above (aircraft reference retained) was the first integrated aircraft to experience this demand for a lightning and HIRF maintenance program, it is relevant to this body of work to describe some of the specific aircraft history associated with the evolution. All critical and essential equipment installed on the airplane were designed to Radiated Frequency (RF) Susceptibility test levels. The airplane uses many necessary and known types of HIRF protection. Flight control systems, displays, engine control systems, and any other critical systems that are susceptible to L/HIRF were analyzed using MSG-3 Analysis for aircraft systems with loss of HIRF protection/shielding considered as a failure cause. This approach, though effective in providing a format to create the maintenance program, was not very well suited to evaluate HIRF and lightning components. Since many HIRF and lightning protection components are designed with redundancy, the maintenance program methodology at the time would conclude that maintenance is not necessary similar to conclusions of those functions that have redundant systems where a single system can fail and not affect the function availability. Unfortunately, a lightning event may not rely on system redundancy since common mode degradation of lightning and HIRF protection components such as corrosion of cable (loom) lightning shields for example, can occur on all shields simultaneously without any reporting to the flight crew of the impending protection failure. For a system that has redundant avionics units, loss of a single unit would be evident to the flight crew through the system health monitoring. An additional complication in lightning and HIRF protection is the possibility that a single lightning or HIRF event can cause system upset across multiple systems or components that may have unknowingly degraded. Therefore, lightning and HIRF protection maintenance is not the same as many system Specific Scheduled Maintenance Tasks based on maintaining adequate L/HIRF protection.

Prior to the MSG-3 methodology revision in 2007, the MSG-3 (Maintenance Steering Group) analysis process was not wholly adequate to address maintenance of lightning and HIRF protection. MSG-3 analysis does not address common-cause failures, especially common-cause latent failures. For example, corrosion on HIRF and lightning shields over flight-critical wiring may degrade the shield's protection effectiveness. This corrosion may occur on all three wire looms of a triple-redundant system. In this case, system redundancy does not provide protection against this kind of common event. A lightning strike to the airplane could induce transients on all three channels of this triple-redundant system. Consequently, common-cause degradation, such as this example shows, can allow lightning strikes to cause a complete loss of function, even though the system had triple redundancy. Unfortunately, since the MSG-3 analysis did not address this type of common failure mechanism, excessive maintenance resulted through the use of engineering judgment; not a very robust or technical approach.

At the beginning of the lightning/HIRF maintenance program development, it was determined that all critical system wiring should be inspected with a General Visual Inspection. This proposal was considered adequate at that time. Arguments against this approach pointed out that the standard general visual inspections used in the past may not detect the protection degradation, because the degradation may occur within connectors, or under the protective jacket of shielded wires. Therefore, the maintenance actions for HIRF and lightning must consider these issues but were ill equipped with the current systems approaches used on other avionics systems to determine appropriate and effective maintenance.

Without a scientific method to address the latent degradation over multiple system redundancies, the OEM created specific HIRF and lightning maintenance programs for the several aircraft under development at that time (specific aircraft reference retained). These programs used modifications to the MSG-3 analysis to identify appropriate maintenance tasks. The OEM is also performing engineering evaluations of the HIRF and lightning protection on airplanes that have been in service, to ensure that the maintenance tasks are detecting and correcting protection degradation. For more recent designed aircraft however, this approach would be unmanageable due to the highly integrated nature of the control electronics on the aircraft.

In an effort to provide a better understanding of the HIRF & Lightning continuing airworthiness issues, the Electromagnetic Effects Harmonization Working Group (EEHWG) efforts developed the HIRF (and Lightning) "User's Manual." This user manual addresses the maintenance, surveillance, repair and modifications of aircraft systems to ensure that HIRF & Lightning protection is not degraded. The user manuals have been used to provide guidance in determining appropriate maintenance but did not offer a revised scientific approach to determining maintenance associated with lightning and HIRF protection component degradation. The guidance within the user's manual provided general theoretical guidance that could be applied by aircraft manufacturers in part. This led to many approaches and sometimes applications of guidance out of context with the document.

The Electromagnetic Effects Harmonization Working Group User's Manuals incorporated significant inputs from the regulatory FAA Aircraft Evaluation Group (FAA-AEG), and AEG counterparts from Transport Canada and the JAA, who continue to work with the FAA Aircraft Evaluation Group (AEG) to ensure that HIRF & Lightning certification requirements are implemented into a maintenance program.

As a result of continuing debates regarding a reasonable approach to determining HIRF and lightning protection maintenance, and industry committee was assembled in 2005 to create a new methodology specific to lightning and HIRF protection. This task force was assembled under the leadership of the Airline Transport Association (ATA) who own the rights to the MSG-3 document publication. Widespread support was provided by many major aircraft manufacturers to this task force resulting in a new methodology agreement in 2007. A more detailed description of the current lightning and HIRF MSG-3 guidelines is contained in the methodology section.

In conclusion, maintenance of HIRF & Lightning protection elements is necessary to ensure that aircraft meet the requirements for continuing airworthiness. Use of the methodology discussed in these case studies will leverage the use of the MSG-3 methodology for lightning and HIRF protection created in 2007.

5.9.8 Lightning Protection Certification Summary

Lightning protection certification relies on submittal of a certification plan to the regulating authority that addresses both direct effects of lightning and indirect effects. For the aircraft under study, the certification for Lightning Direct Effects has been submitted is in accordance with FAA AC 20-53A [5.1]. This submittal is critical to the methodology exercised in these case studies, since declaration of the important elements of the direct effects protection is included in the certification plan. For the aircraft in this case studies, the certification for Lightning Indirect Effects is in accordance with FAA AC20-136 [5.2]. This certification plan is also critical to use of the methodology in the case studies since it provides the important elements of lightning protection indirect effects.

Both the indirect effects and direct effects certification plan are included in a single certification report supplied to the FAA [5.32]. This is supplied to comply with the FAA and JAA requirements for indirect effects lightning protection (FAR 25.1316 and CRI F-03) [5.54], airplane systems that perform critical and essential functions must be demonstrated to operate safely in the defined lightning environment. It is also supplied to the FAA to comply with FAA and JAA requirements for direct effects lightning (FAR 25.581, 25.954 and JAR 25.581, 25.954, 25.899) and P-Static protection, confirming that aircraft structure exposed to lightning and P-Static is shown to be immune to the defined environment.

The aircraft level lightning waveforms of AC20-136 are used to derive the indirect effects or induced transient levels coupled into equipment circuits and wiring. The induced transient levels for equipment are in the OEM document (Document reference retained) [5.33] and applied to equipment analysis, design and test. This document contains the electromagnetic compatibility requirements of electrical/electronic equipment selected for installation on the OEM commercial transport airplanes. Transient, audio frequency, and radio frequency limits of emissions and susceptibility are specified for the equipment. Test procedures, typical test set-ups, approved measuring equipment and test provisions are included along with designer's notes to assist in proper interpretation of design and test requirements. EMC Test Procedure and Test Report data requirements are also specified. Various test procedures in this document [5.33] have been updated and clarified, with additional attention given to requirements for supporting documentation. Several requirements have been revised to be consistent with RTCA/DO-160 (latest revision and change notice). The term “electromagnetic compatibility” or its abbreviation “EMC” is used to refer to the process and discipline for addressing all electromagnetic effects, including transient, audio frequency, and radio frequency emissions and susceptibility. The term encompasses electromagnetic effects resulting from lightning, high intensity radiated fields, electrostatic discharges, or airplane equipment operation. This clarification is necessary since many design engineers refer to EMC as the protection of equipment from emissions caused by other equipment. For the aircraft design, the term EMC is used to represent several electromagnetic threats.

Electromagnetic compatibility requires that each airplane system perform its intended function in the airplane electromagnetic environment, and that the operation of a given system does not degrade the performance of other airplane systems. Airplane electromagnetic compatibility requires appropriate airplane structural design, equipment installation, wiring installation, and equipment qualification. The limits of emissions and susceptibility thresholds contained in the EMC Test Procedure [5.33] document are a means of assuring that the design objectives will be achieved when compliant equipment is installed on an airplane. The methodology used in the case studies is proposed to ensure that this protection provides a way to ensure that the compliant equipment is meeting its design objectives throughout the life of the aircraft.

The EMC Test document [5.33] contains the electromagnetic compatibility qualification and documentation requirements for electrical/electronic equipment that will be installed on the OEM commercial transport airplanes. Transient, audio frequency and radio frequency limits of emissions and susceptibility are specified for the equipment. Test procedures, typical test set-ups, approved measuring equipment and test provisions are included along with designer's notes to assist in proper interpretation of design and test requirements. EMC Test Procedure and Test Report data requirements are also specified.

Failure Condition Classifications: The failure condition classifications listed below are derived from FAA/JAA regulations and advisory material (e.g., FAR/JAR 25.1309) and are included to assist in understanding the source of protection component identifications needed by the case studies methodology. These classifications are also shown in SAE Document ARP5413 [5.20].

Catastrophic: Failure conditions which would prevent continued safe flight and landing.
Hazardous / Severe – Major: Failure conditions which would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be:

- A large reduction in safety margins or functional capabilities.

- Physical distress or higher workload such that the flight crew could not be relied on to perform their tasks accurately or completely, or
- Serious (or fatal (JAA only)) injury to a relatively small number of the occupants.

Major: Failure conditions which would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example, a significant reduction in safety margins or functional capabilities, a significant increase in crew work load or in conditions impairing crew efficiency, or discomfort to occupants, possibly including injuries.
Minor: Failure conditions which would not significantly reduce aircraft safety, and which involve crew actions that are well within their capabilities. Minor failure conditions may include, for example, a slight reduction in safety margins or functional capabilities, a slight increase in crew work load, such as routine flight plan changes, or some inconvenience to occupants.
No Effects: Failure conditions which do not affect the operational capability of the aircraft or increase crew workload.

Development Assurance Levels

The following Development Assurance Levels relate to the failure condition classifications listed above. These levels are also in SAE Document ARP5413 [5.20].
Level A: Electrical and electronic systems whose failure would cause or contribute to a failure of function resulting in a catastrophic failure condition for the aircraft.
Level B: Electrical and electronic systems whose failure would cause or contribute to a failure of function resulting in a hazardous / severe-major failure condition.
Level C: Electrical and electronic systems whose failure would cause or contribute to a failure of function resulting in a major failure condition for the aircraft.
Level D: Electrical and electronic systems whose failure would cause or contribute to a failure of function resulting in a minor failure condition for the aircraft.
Level E: Electrical and electronic systems whose failure would cause or contribute to a failure of function resulting in no effect on aircraft operational capability or crew workload.

For the test of equipment to meet EMC requirements, the following elements are included in the EMC Test Report. It is recommended by this work that the EMC Test Report and design criteria be amended from this original list of test report criteria to include the continued airworthiness protection assurance. (The additional design data required is listed in item 13 below.)

1. A table summarizing the tests performed, stating whether or not the test results successfully met the requirements of this document, and providing page numbers pointing to or referencing the supporting data.
2. A description of the quality assurance used during the test, with the report signed by the supplier quality assurance representative.
3. Copies of completed FAA conformity forms 8130-9 and 8100-1 for the equipment under test and for the test setup.
4. Any changes to test procedure, layout or test parameters previously authorized.
5. Nomenclature and serial numbers of test equipment used, together with most recent calibration dates of interference measurement equipment.

6. Photographs (with labels) of each test setup. Written description may be used to supplement the photographs.
7. Equipment under test identification, including complete nomenclature, manufacturer, part numbers, and serial numbers, together with a description of the equipment function, its intended use and installation.
8. Where applicable, test results in graphical (X-Y) form with units as specified herein for each test. Plotter outputs, photographs, or hand-plotted data should accompany tabulated test data to facilitate review. All critical parameters used to record data (bandwidth, scan rate, etc.) shall accompany data. Thresholds of susceptibility shall be recorded.
9. Test limits shown such that compliance or noncompliance is evident. Photographs from a spectrum analyzer are acceptable provided that the applicable test limits are clearly legible.
10. A description of modifications to equipment incorporated during test.
11. A list of antenna correction factors, current probe transfer impedance, and other correction factors used for data reduction.
12. Similarity rationale and analyses shall be included in the report.
13. **Completion of continued airworthiness assessment forms and submittal including protection design change recommendations where appropriate.**

Equipment Categories for EMC

Electrical and electronic equipment shall be classified by category for purposes of assigning applicable electromagnetic tests and may generally be characterized by one of the four EMC categories given below. Note, however, that unless otherwise explicitly defined by the applicable procurement specification, Category 4 shall apply. Certain tests (e.g., RF susceptibility and lightning) detailed herein will utilize test levels determined by equipment location and criticality level. For equipment having requirements for these tests, the applicable procurement specification should provide the required test level(s). The interpretation of criticality for equipment that requires EMC protection is in the Table 5-20.

1. Category 1 - Non-electronic equipment or systems which may exhibit non-repetitive transient emissions, and which do not require susceptibility testing. Generally equipment of this category is passive in nature and capable of utilizing airplane power directly without the requirement for further conditioning. Examples of items in this category include DC relays, DC solenoids, and brushless induction motors.
2. Category 2 - Non-electronic equipment or systems which may exhibit emissions, and which do not require susceptibility testing. This equipment generally contains components for conversion of power which utilize brushes, diodes, etc. Examples of this category include AC operated relays and solenoids, AC operated valves, motors (with brushes), generators and fluorescent lamps.
3. Category 3 - Electrical/electronic equipment, generally classified as Non-Essential, and which may exhibit susceptibility to wire-coupled and/or radiated electromagnetic interference.
4. Category 4 - Electrical/electronic equipment, generally classified as either Critical or Essential, which may exhibit susceptibility to wire-coupled and/or radiated electromagnetic interference.

EMC Category	Criticality	Failure Condition Classification	Development Assurance Level
4	Critical	Catastrophic	A
4	Essential	Hazardous / Severe – Major	B
4	Essential	Major	C
3	Non-Essential	Minor	D
2	N/A	No Effect	E
1	N/A	No Effect	E

Table 5-20 System Criticality & Development Assurance Levels

Identification of critical and essential functions establish the Electromagnetic Compatibility (EMC) categories, lightning design and test levels, and pass/fail criteria which are consistent with allocated shielding in internal and external areas of the aircraft considering equipment location, shielding, transient protection, and effects on safety of flight. Critical systems are defined with Design Assurance Level of "A" and are systems whose failure would cause or contribute to a failure or function that would prevent continued safe flight and landing. Essential systems are defined with Design Assurance Level of "B" and are systems whose failure reduces the capability of the airplane or ability of the crew to cope with adverse operating conditions

Structures and systems installation similar to those on certified, in-service aircraft developed by the OEM and located in equivalent areas have been verified for direct effects lightning certification by similarity. Non-metallic structures covering flight critical control components and cabling have been verified by analysis and/or engineering tests to prevent puncture by lightning. Engineering tests will use waveforms of Appendix 3 of AC 20-53A [5.1] applicable to the location of the non-metallic structure. The identification of the Development Assurance Levels for equipment on the aircraft in the case studies are used to define the appropriate components for wiring and equipment to be evaluated during the design phase using the methodology developed within this body of work.

5.9.9 Equipment Qualification Requirements and System Protection Design

Critical and essential equipment installed on the airplane are designed to electromagnetic requirements as indicated in the aircraft HIRF/Lightning Certification Plans for lightning [5.40] [5.32], the General Technical Requirements (GTR) for the specific aircraft type [5.41] and the individual equipment specifications distributed throughout the design development program experts. This equipment will be compliance tested in accordance with D6-16050-4 [5.33], which is consistent with the intent of RTCA DO-160C document [5.3]. The Lightning requirements for equipment were established to be consistent with the protection provided by airplane structure and wire shielding. Test levels for equipment qualification will be shown by analysis and test to be equivalent to the levels induced by external HIRF or lightning on, or at the equipment, as installed in the airplane.

Electromagnetic compatibility requires that each airplane system perform its intended function in the airplane electromagnetic environment, and that the operation of a given system does not degrade the performance of other airplane systems. Airplane electromagnetic compatibility requires appropriate airplane structural design, equipment installation, wiring installation, and equipment qualification. These protection systems may require additional design development if they are determined to be inadequate over the life of the aircraft. The limits of emissions and susceptibility thresholds contained in the OEM requirements are a means of assuring that the design objectives will be achieved when compliant equipment is installed on an airplane. The specific OEM requirements document [5.33] is drafted using the industry standards from RTCA DO-160 [5.3] as an initial requirement baseline. The OEM document, “Electromagnetic Interference Control Requirements” [5.33] contains the electromagnetic compatibility qualification and documentation requirements for electrical/electronic equipment that will be installed on the OEM commercial transport airplanes.

Each supplier to the OEM has full responsibility for the EMC design, construction and testing of furnished equipment. This effort shall be in accordance with the applicable procurement specification and this document. This shall include the responsibility to design into all circuitry and associated packaging proven and effective techniques for control of emissions and susceptibilities. Although the test procedures and methods detailed standardized, each supplier has the responsibility of demonstrating that the performance of each unit is tested and exercised with the hardware, interfaces, software, and modes of operation representative of the actual in-service installation. Test equipment and load simulation units shall be designed for RF immunity and susceptibility-free monitoring to ensure accuracy of measurements.

Qualification of system components and electronics are governed by the design leaders for the aircraft development project. The typical guidance for component development qualification is the FAA Advisor Circular AC20-136 [5.2]. Within this guidance, the Equipment Transient Design Levels (ETDL) defines the equipment immunity thresholds and is used as qualification design and test levels for the OEM aircraft equipment suppliers. The ETDLs and test procedure are described in the OEM document (reference retained) [5.33] to complete the required qualifications. The test levels for aircraft equipment in the case studies are established by the project leaders and provided to the equipment manufacturers to ensure that appropriate lightning protection capabilities have been designed into the system equipment. The test levels adopted by the aircraft design team are provided in Table 5-21 and reference the locations where wiring may be external to the pressure vessel or internal to the pressure vessel. The use of requirements for testing equipment is important to the functioning and continuous operation of the equipment, both during and after a lightning strike event. The transients that are generated by lightning strikes can threaten continued safe operation of the mission equipment and the aircraft. Qualification testing of the equipment is a measure to ensure that the identified equipment is proven to be able to withstand lightning strike transients while operating on the aircraft. This testing does not ensure that an aircraft system is immune from lightning strike damage or system interruption, but does provide a means to define the lightning protection installed on the aircraft as the requirements for these qualification procedures are distributed to equipment manufacturers. The requirements generated by the OEM and distributed to equipment suppliers contain the electromagnetic compatibility standard for electrical/electronic equipment selected for installation on the OEM commercial transport airplanes. Transient, audio frequency, and radio frequency limits of emissions and susceptibility are specified for the equipment as well. Test procedures, typical test set-ups, approved measuring equipment and test provisions are included along with designer's notes to assist in proper interpretation of design and test requirements.

EMC Test Procedure and Test Report data requirements are specified by the OEM for development and submittal to the regulatory authorities at the time of certification.

Test Requirement	External Wiring	Internal Wiring
Ground Injected	600V/120A	N/A
Pin Injected	600V/120A	N/A
Cable Injected	600V/120A	N/A
Multiple Burst	300V/60A	125V/25A 60V/12A

Table 5-21 Aircraft Lightning Transient Design Test Levels

To manage the design of lightning protection across all avionic and electrical systems, an EMC Assurance Plan is required from each OEM.

The equipment design proposal from suppliers includes an EMC Assurance Plan which details the overall approach, design procedures and techniques that will be used by the supplier to meet the EMC requirements.

The information that is important to the design of lightning protection for systems is delivered prior to the preliminary design review and addresses, as a minimum, the following items:

a. Organizational responsibilities with respect to EMC. This should include information as to responsible EMC design, analysis and test engineering contacts, and names of individuals responsible for support of design reviews and EMC documentation. A schedule of EMC events or milestones shall be included, along with a detailing of known contractual EMC requirements for the unit(s), and a summary of EMC requirements passed to or levied upon subcontractors by the supplier. All applicable EMC documentation shall be identified, together with all EMC specifications (and versions thereof) which are to be used in design.
b. A concise description of operational parameters of the system and its intended installation. Identify, for example, which portions of the system are contained within the various component units, which are external, estimated separation distances, and mounting considerations.
c. A summary of mechanical design as related to EMC. Materials should be described, as well as procedures and methods to be used for purposes of

attenuating electromagnetic emissions and/or reducing susceptibilities of equipment to the specified electromagnetic threats. A description should be given of internal shielding and filtering methods used to achieve compliance. Mechanical drawings may be used to identify the locations and physical characteristics of possible apertures, electrical connectors and panel mounted components, and design details of RFI gaskets (if used) should be given. Filter characteristics and/or component values of power line filters should be provided, if used. If filter pins are to be employed in design, the attenuation and/or peak limiting characteristics should be included. A description of construction materials employed in design should be given. Bonding surfaces should be identified, together with what, if any, surface treatment is used for purposes of achieving compliance with applicable bonding specifications.

d. Diagrams or descriptions of all supplier-provided wiring and/or cable design required to minimize emissions and susceptibilities. Choice of wire type and wire treatment (twisted, twisted-pair, shielding, etc.) and wire routing methodology should be provided. Wire separations or special treatment of wires identified as being either susceptible to EMI or capable of being a source of interference, and isolation or other method(s) used to achieve compliance should be given. Technical criteria should be provided to justify usage of cable shields or filter pins.
e. A description of grounding methods. A grounding diagram may be used to show the methods by which overall grounding, treatment of power and signal returns, and power distribution within or between individual units of system is achieved.
f. Potential sources of interference or susceptibility. A summary of clock frequencies, data rates, intermediate frequencies, and frequencies of RF carriers utilized in the design should be provided as applicable.
g. Known or anticipated lightning, HIRF and/or EMC problems. Both a description of procedures to be used for analyses and a summary of proposed solutions to interference problems should be given.

Engineering requirements for the connectors used in system shielded wiring for the aircraft in the case studies are expressed in terms of maximum transfer impedance (as a function of frequency) which should not be exceeded during an airplane's service life. The assurance that the ‘end of life’ values for impedance on protective wire shielding is valid can be provided more effectively by use of the methodology. The transfer impedance associated with a particular wire loom design relates the induced voltage on the core wires to the current flowing on the shield. At low frequencies, below about 1 kHz, the transfer impedance or the transfer resistance is equal to the resistance measured from shield through the connector to the airplane structure where the receptacle is mounted. At higher frequencies the transfer impedance is complex and is related to how the core wires are exposed to the magnetic fields which leak through small apertures and openings in the shield surrounding the core wires of the wire loom. The higher frequency transfer impedance (often described by a transfer inductance value) is mainly controlled by connector and braid geometry and style. Using values for transfer impedance known to exist on other aircraft produced by the OEM in these case studies, the design group responsible for determining the shielded required calculates impedance and translates this impedance to a specific shield design for critical wire looms. These wire looms that contain protective features such as shield wires, connector bonds, system LRU conductive attachments to the airplane structure and sometime bonding jumpers, all must remain effective over the life of the installations.

For a lightning strike protection on wire looms to be effective, the wire loom design must include appropriate transfer impedance across all the system connections to the aircraft structure. This also includes required “stand-off” impedance at the system electronics interface to the wire looms. The aircraft in the case studies wiring approach provides sufficient wire shielding to protect the aircraft systems from electromagnetic environments by a combination of wire loom protection and internal protection within affected electronic system line replaceable units over normal lightning frequency ranges. The cable shield exists in addition to LRU box protection in most cases. The aircraft wire shielding baseline design is to shield all wiring external to the pressure vessel with one layer of shielding and terminate both ends of the shield with a 2 inch bond wire to the connector back-shell. The only exceptions were for wires routed near the top of the bays in the air-conditioning bay and wheel wells. For these wires, shielding was added on a case by case basis depending on the geometry of the wire routing. In addition, all wires associated with critical systems and within 1 foot of the flight deck windows have a single layer of shielding with the shield terminated at both ends with a 2 inch bond wire to the connector back-shell.

As with most design processes, the lightning protection implemented on the aircraft in the case studies have some improvements from lightning protection on past aircraft produced by this OEM. The most significant design process improvement that was made for the aircraft wiring studied in this case was the incorporation of many electrical bond checks upon installation of the bond for certain critical wiring. These bonds are referred to as “designated” bonds on the aircraft drawings. Upon final installation, all connectors and wiring that contain lightning protection elements are checked for appropriate resistance between receptacle and aircraft structures in which they are mounted. This was not required on previous models. In addition, the following improvements are incorporated on the aircraft in the case studies and are deemed significant:

1. Key bonding locations are tested upon installation to ensure that the bond is present. These are called “designated bonds”. All shield termination connectors where receptacles are used to ground shields have designated bonds. Special notes have been included in the wiring production digital data base which identifies shield grounding for each wire loom. Verification procedures are included in the OEM design specifications for bonding and grounding.
2. All critical lightning protected connectors contain spring fingers within the design to improve conductivity. Spring fingers have been incorporated into the plug connector to make the electrical connection through the "spring fingers" and not rely on the connection made via threads in the connector. In-service testing of an aircraft developed by this OEM concluded that the connectors measuring the highest resistances and in most cases above resistance limits, were the threaded connectors, without spring fingers.

3. Bond wires are used to terminate shields to the connector back-shells. All shields are terminated by a 2 inch bond wire to the connector back-shell. This eliminates the zero length back-shell used on a different aircraft developed by this same OEM which caused some maintenance problems.
4. Back-shell mating viewports were added in the back-shell to allow visual check of connector connection. This is a significant improvement over existing designs as it allows the technician to assess and judge the connections on the connectors immediately after installation without a bond meter. Proper electrical connections between the teeth of the connector which interlock the connector and back-shell may be difficult to determine. The viewport allows the assemblers to verify their work. The viewport makes people aware that the proper connection of the mating connectors is an important step in the assembly.

Incorporation of these design improvements and features is one way to ensure that the aircraft is protected from the potentially hazardous effects of a lightning strike. The continued assurance of these protection features can only be measured after many performance cycles. During the design of an aircraft, the protection is tested to ensure that it will meet the requirements to protection critical systems on the aircraft in flight. These tests are usually performed with the initial protection function in mind and do not seek to ensure the long lasting effectiveness once a protection system is out into service. The purpose of this body of work is to create a new aircraft design methodology in order to address the cited design concerns. In addition to reliance on initial design practices, the OEM has instituted an Assurance Plan [5.49] to address the long term effectiveness of lightning protection.

5.9.10 Lightning Protection Design Assurance

Designers of lightning protection may choose to establish assurance plans for evaluating the long term effectiveness of lightning protection design features built into the aircraft in the case studies. An assurance plan can consist of planned testing in the factory and in operation at airline facilities. The benefits of such a plan may manifest in improved rationale for scheduled and unscheduled maintenance activities defined and implemented by the aircraft Maintenance review Board (MRB) Report and related Maintenance Manuals. Results of on-going testing within an assurance program can be collected and used in future design processes as part of the assessment sheets proposed by this body of work.

The assurance plan defines techniques and requirements for assuring that the specific aircraft protection is adequate at the time of installation and remains effective as the aircraft ages. The plan addresses the approach to preserving HIRF and lightning protection integrity of the specific airplane. A document with details regarding the Assurance Plan [5.49] is submitted to the FAA as part of the aircraft type certification to show compliance with Issue Paper M-2 and FAR/JAR 25.1529, "Instructions for Continued Airworthiness", as applied to FAA Issue Papers E- 1, FAR 25.1316 and JAA CAI 05-11. It is the intent of the assurance document to work in conjunction with the specific aircraft Maintenance Review Board Report [5.52] document which details scheduled maintenance of the HIRF/Lightning protection designs. The scheduled maintenance outlined in the MRB report is supplemented by the Assurance Plan. The two programs substantiate and complement each other.

An Engineering Validation Program is outlined in the Assurance Plan document [5.49] which provides a description of both pre-delivery testing and in-service protection validations. The "Aircraft (type retained) HIRF/Lightning Protection Assurance and Validation Test Plan" [5.50] contains detailed test plans and procedures for factory, flight test and in-service validation tests including final wire loom selection and test methods. The intent for testing aircraft in the factory and in service is to follow the same aircraft from the start of assembly in the wire shop, to factory testing of wire looms, and finally to an in-service validation testing program of specific aircraft. The purpose of these inspections is to:

1) verify assembly processes are under control and produce a quality product
2) capture/minimize infant mortality
3) establish a performance baseline for eventual in-service sampling
4) assess the health of the wiring and shielding characteristics during the life of the specific aircraft type and the adequacy of the scheduled and unscheduled maintenance of those lightning protection features

The inspections consist of measurements of shielding performance parameters, such as shield resistances, in the wire shop where cable looms are assembled and the factory where looms are installed. The data will be tracked in a database containing information such as: shop and factory resistances per loom assembly, system categorization for each loom, type of termination, nearest LRU, nearest disconnect bracket, nearest structure access panel, etc. This data is necessary to establish degradation trends and to ultimately establish reliability information.

Consistent with the regulatory requirements, systems covered by the Assurance Plan [5.49] include critical and essential systems that could be affected or influenced by lightning or HIRF effects. Engine control system protection features incorporated by engine manufacturers to meet HIRF and lightning requirements, are not addressed by this plan, however engine control wiring from the engine strut disconnect to the electrical equipment bay will be sampled as part of this validation program. Both airline maintenance and any validation efforts for on-engine protection are separately addressed by the engine manufacturers.

5.10 Purpose of the Case Studies

The primary purpose of the case studies is to exercise the methodology contained in this body of work using actual aircraft data. In order to adequately exercise the methodology, the case studies address both direct effects lightning protection and indirect effects lightning protection.

The goal is to assess alternatives and determine the validity of the methodology, practical application of the methodology and potential improvements to the approach. Although created for lightning design engineering, this methodology could apply to other design functionality assessments. For example, the choices for any design alternative can be evaluated using this methodology to examine functions, designs, support concepts, manufacturing approaches and type certification decisions. The task undertaken by performing these case studies is to collect and create the data required to make design decisions while integrating and balancing a variety of considerations such as feasibility, performance, producability, testability, compatibility, reliability, system safety, maintainability, and supportability.

5.10.1 Other Application of the Methodology

The methodology can be used to evaluate costs, though this was not an initial consideration. Important objectives for this process are clarification of options, problem structure, and available trade-offs; improved communication of ideas and professional judgment; improved communication of rationale for action to external stakeholders; confidence that all available information has been accounted for; clear documentation of the results and recommendations; and integration of multidisciplinary inputs.

5.10.2 Demonstrated Capability

With this methodology in place, the case studies demonstrate that designs can be optimized if the methodology is implemented. Key to successful implementation of the methodology is the ability to improve decision making when determining the best alternative for lightning protection designs. Another outcome of the case studies is to prove through the exercise that sustaining an appropriate safety margin and safety commitment established by the design team can be one outcome of the lightning protection assessments proposed by the methodology. Once the assessment is in an acceptable configuration, then appropriate maintenance decisions can be made depending on the design assessment conclusion. And finally, the case studies are also intended to show that effective type certification can be achieved by use of the methodology within a lightning design program.

5.11 Case Studies Approach

The case studies within the sections of the thesis included a variety of lightning protection to exercise the methodology. The case studies documents a standard methodology and exercises the methodology through use of actual aircraft lightning protection data for assessing alternatives and deciding on a preferred approach concerning lightning protection deployment at different locations on the aircraft. These case studies also address both direct effects lightning protection and in-direct effects lightning protection. Four different lightning protection designs were evaluated with assessment sheets to exercise the methodology.

In order to acquire the information needed for the case studies, access to installation drawings, wire diagrams, specification documents and certification documents is necessary. With access to this information, key lightning protection details are collected and included in the assessment sheets. During a design development program, data can be collected as design decisions are contemplated and a feedback can be provided to improve the final design configuration.

To perform a well-functioning design evaluation system, the case studies included a plan for assessments; purpose statement, identification of decision authority for acting on the recommendations, description of key assumptions, list of evaluation criteria, alternatives selected for the evaluation, and evaluation methodology.

Also included in the case studies is a reflection on design systems, association of the design decision making to the methodology and also evidence through literature research that poor design decisions associated with lightning protection can cause unwanted events. The case studies identify the method (s) for performing the design evaluations which includes the use of a design assessment sheet. Four different lightning protection designs were included in the case studies. Repeated demonstration of the methodology beyond these four assessments was not deemed necessary as a repeat of the process would demonstrate similar findings. The case studies also established success criteria to characterize how to evaluate lightning protection designs, categorize the protection types and provide meaningful recommendations. The approach will use insightful evaluation methods such as rating tables for area environmental threats, hardware specifications, and aircraft location design requirements for temperature, vibration and moisture, etc. The method and measures most appropriate to the main objective of the case studies are collected within the assessment sheets. These measures included drawings, bond path definitions for each lightning protection element selected for the studies and galvanic tables to define the potential of each design to degrade within the environment of its installed location. The evaluation criteria for the case studies are included in the assessment sheets. These case studies demonstrate the ability to analyze information that is readily available to a designer. It was not intended to create new data but rather prove that already existing data can be used to perform the design evaluations. Though the case studies are intended to perform a "performance-focused" evaluation, further expansion of the studies could be developed by inclusion of cost, availability and weight associated with any lightning protection component. The case studies exercised design decisions based on the evaluation of data including key points for selection or rejection of alternatives.

The case studies start with the discussion on aircraft design processes. In order to understand how the new aircraft design methodology can be implemented a discussion about the design phases and topics are included in the case studies. Lightning strike probability and location is defined in order to understand some of the key areas where lightning strike protection is necessary. Specific discussion about the design zones of the aircraft and threats imposed on systems within each zone is discussed. Lightning protection of many types are included in the case studies. Categories of different protection are developed to help organize the case studies. Data for each detailed analysis of lightning protection is included after the assessment sheets. Each lightning protection component that is incorporated in the assessment sheet is also described in detail along with a description of the installation associated with the lightning protection. Much of the data gathered within these case studies are found in the figures after the assessment sheet.

From the completion of the assessment sheets in this case studies, it was determined that a single integrating entity within the design community might be the best choice for leading the design assessments. Skills in understanding materials test and performance of components in a multitude of environments is needed to perform the assessments. It is best to create a tool for conducting the assessments and organizing the interfaces with the other design team members. For this, a database may be helpful to create a more efficient and integrated solution. Within the design assessment conclusions, a committee may be formed to address cases where multiple disciplines will be required to make input to the final design solution.

5.12 Case Studies Data Discussion

For this research, the analysis of the design performance associated with the proposed methodology is restricted to theoretical studies for a potential design approach. Actual evidence of the effectiveness of the methodology and its associated tool are theoretical and do not reflect any known design methodology.

List of Critical and Essential Systems (See Appendix C and Appendix D):
As the methodology presented in the case studies requires certain qualification data, the method for qualification of equipment installed on an aircraft is relevant to understanding the source of the necessary data to support regulatory approval. For the aircraft in these case studies, there are several different approaches to qualification of the systems which causes the methodology to acquire the needed data from several sources.

A description of each critical and essential systems is provided in the Appendices for ease of review (these appendices are proprietary). The first column provides the ATA chapter associated with the System. The ATA chapter is needed only for performing searches of the OEM customer data bases needed to develop the service history of existing equipment.

The categories of data contained in the "Qualification Method" qualification are as follows and are found in Table 5-22 with the aircraft type references retained (Aircraft A = 3, Aircraft B = 7, Aircraft D = 4, Aircraft E = 5, Aircraft F = 6):

Qualification Method	Aircraft Type	Approach Used	Reasoning
Certification	A	Original previous model aircraft certification results	Indicates existing equipment currently installed on specific airplanes. A service history discussion to certify that the equipment for the Aircraft "A" was provided to the regulatory authority for substantiation of those items on the list.
Qualification	B	Use aircraft B qualification data for systems that are similar on this aircraft	Aircraft "B" Systems and Equipment qualified as part of the Aircraft "B" development program. Aircraft "B" qualification data is used to qualify these systems/equipment on the aircraft after verification that the wire shielding configuration used in the Aircraft "B" qualification test is equivalent (or worse) than the aircraft installations in these case studies.
Multiple aircraft certifications	B, D, E, F	Use of data from several past certifications of aircraft development programs	This qualification method applies only to the ADF Active Antennas. These active antennas are proposed to be certified by service history. The only difference between the antennas on the aircraft in the case study that addresses antenna installations and the antennas on the above aircraft is the fastener type. The antenna made by one antenna OEM has 19.4 million flight hours on the above aircraft; the antenna made by another OEM has 12.1 million flight hours. There are no known upsets in service due to HIRF or Induced Lightning on these active antennas. As for direct effects lightning, per an OEM study that acquired strike history back to 1985, the aircraft fleet (aircraft type retained) has not taken a lightning strike to the ADF antennas.

Qualification Method	Aircraft Type	Approach Used	Reasoning
Analysis	N/A	Use of analysis of system architectures.	This qualification method applies only to electrical panels containing the Universal Master Caution (UMC) card.
Test	A	Test systems and components	The category of "Test" indicates that a full qualification test was performed on the systems/equipment for the aircraft in the case studies.

Table 5-22-Systems with possible catastrophic failure mode(s) due to HIRF/Lightning certification methods

Note that only two "Qualification Methods" are used for systems/equipment with catastrophic failure modes: Qualification and Test. That is, there are no systems with possible catastrophic failure modes that are qualified by service history or by analysis.

There are 6 pieces of systems/equipment using Aircraft B qualification data: one Display Unit, two Instrument Landing Systems (ILS), and three Low Range Radio Altimeters (LRRA). Aircraft B qualification data is used in conjunction with the airplane data in the case studies to show compliance to HIRF and Lightning external environments for JAA certification. Aircraft B qualification data is used directly to show compliance to HIRF and Lightning for FAA certification. There are 9 pieces of systems/equipment where a full qualification test is performed for the aircraft in these case studies.

All systems with possible catastrophic failure modes due to HIRF/Lightning events were tested per the intent of a system-level test: an integrated test rig with all support equipment that exercised all system-level functions while monitoring for any system-level failure modes.

Note that all five qualification methods are used for this type of equipment: Aircraft A Certification and Aircraft B Certification, Aircraft B Qualification, Airplane Certification Airplane Test and Airplane Analysis of the aircraft under study.

Equipment Qualified by Aircraft A Service History (Aircraft A Cert)

Explanation of qualification methods:
There are 29 pieces of equipment utilizing "Aircraft A Service History", as a qualification method. This equipment is proposed to be qualified for installation on the aircraft in these case studies due to at least 3 years of installation on an Aircraft A without a HIRF/Lightning incident causing a hazardous/major failure mode. Three years was chosen as the minimum acceptable time for adequate service history based on the following rationale. The number of Aircraft A airplanes delivered from March 1994 to March 1997 was 277.

From airline reports to the OEM, the Aircraft A fleet averages for the total number of flight hours from March 1994 to March 1997 was found to be 1,284,641(1.28 E6).

The total number of equivalent airplanes in service during this three year period is found from the total number of flight hours:

$$\frac{(1.28\text{ E6 airplane hours})}{(365\text{ days})(7.83\text{ hours/day})} = 448\text{ airplanes}$$

<u>Lightning Strike Flight Statistics</u>
Lightning flight statistics can be related to the number of flight hours. From standard literature provided earlier in this body of work during the discussion of the lightning phenomenon (reference Chapter 2), an airplane lightning strike occurs once every 2.5 E3 hours and a worst case, 200 KA lightning strikes occur about 1 % of the time. Thus, in the last three years:

1.28 E6 total airplane hours / 2.5 E3 hours/strike

= 512 airplane lightning strikes (or 5 worst case lightning strikes in the proposed three year period)

For the certification of the aircraft used in the case studies, the exposure to over 5 hundred strikes and 5 worst case strikes is considered an adequate threat for modeling protection for essential equipment. It is clear from the lightning strike probability and the number of aircraft that are in service, that the use of real events which may result in catastrophic or hazardous conditions are the central argument of the certification proposal. The main concern with this approach is that an assumed continued airworthiness condition cannot be used to make long-term decisions regarding selection of protective equipment since the absence of a major event is only proof that from a probabilistic perspective, the worst case lightning strike has not occurred on an aircraft that has the worst case degradation of its lightning protection. Maintenance on the aircraft can sustain some of the design standards as protection components are replaced or possibly tested as part of equipment replacements. This body of work proposes that an approach to design where past experience is the only factor in determining the adequacy of protection is not an optimal approach to creating the best performing designs.

The Service History Approach

To determine what existing equipment had at least 3 years of acceptable service history on the certification exercise for the aircraft used in the case studies, the following describes the approach that was used. After developing the list of existing equipment, the equipment's function and possible failure mode of the function due to a HIRF/Lightning event was acquired from equipment managers and designated engineering representatives. Keywords from the data in the "possible failure mode" column and the words "HIRF", "Lightning", and "EMI" were used as search criteria for OEM customer data bases: the Schedule Interruption Data System (SIDS); the Significant Item Reporting System (SIRS); and the Airline Maintenance Log Data Base. Searches were then performed by ATA chapter and were limited to the last five years of data base information.

Use of data from known equipment performance databases within the aircraft designer organizations is a strategic approach to minimizing the retesting of critical equipment to prove integrity of designs during a new aircraft development program. This approach minimizes expensive testing and creates a more effective way to certification for certain equipment that has known robust performance. The challenge with this approach which is addressed by the postulated methodology within this body of work is that specific protections against the potentially adverse effects of lightning often fail in a latent manner and do not result in functional effects on the equipment unless the protection is severely degraded and a lightning strike of high intensity attaches to the aircraft in flight. The ability to prove that service experience is a determining factor for design adequacy is overlooked in this case. Instead, an assumption of the adequacy of the protection designs is loosely correlated to the performance of the critical and essential equipment from an operational perspective. A brief description of these data bases follow:

Schedule Interruption Data System
SIDS contains data for events which cause schedule interruptions (delays, cancellations, air turnbacks, diversions) for the entire OEM in-production fleet and includes all operators. SIDS data sources are Airline Reports and Telexes or communications from operators of OEM aircraft.
Significant Item Reporting System
SIRS contains data for airplane events and items deemed "significant" for all OEM aircraft. Incoming daily correspondence from the customer service representatives are the primary SIRS data source; however, Airline Reports and Service Deficiency Reports (SDR) from the FAA may also be included. This data source is limited to safety or extended twin operation performance events after March 1993.
Airline Maintenance (Log Books)
Log Books contain detailed records of all pilot reports and line maintenance actions (unscheduled line maintenance events) performed on the aircraft from a sample of airlines. The equipment manager or designated engineering representative then reviewed all findings from these data bases, determined if any findings were due to HIRF/Lightning, and confirmed that no HIRF/Lightning findings were associated with possible hazardous or major safety concerns. Thus, the set of existing equipment has acceptable performance to HIRF/Lightning in the last five years. What still needed to be determined was whether recent equipment installations had voided five years of acceptable performance for particular equipment's installation record. Therefore, the equipment manager or engineering representative provides the date of installation for the last significant change of their piece of existing equipment.

Based on the rationale presented above, the OEM established an argument that existing equipment for the aircraft in the case studies has adequate service history with respect to HIRF and Lightning for certain certification exercises. Therefore, no re-qualification tests are necessary for equipment where the OEM has determined that past experience is an adequate demonstration of the expected equipment performance. As aircraft designs become more advanced and complex, the use of an argument regarding service experience will be more challenging. To declare equipment as effective in meeting the intended purpose, this work suggests that previous experience may need to be augmented with a more robust evaluation using known degradation modes and equipment installation details during the aircraft design phase. The analysis sheets demonstrated in the case studies provide one way to deploy the evaluation.

Equipment Qualified with Aircraft B Data are referenced in the table with the notation, “Aircraft B Qualification”. These are equipment on the aircraft in the case studies that were qualified using the Aircraft B qualification data as noted in the tables in Appendix C and Appendix D. During the development of an aircraft program, it is important to know what qualifications will be used to represent the design contemplated in order to make appropriate investigation into previous qualification test results. As these qualification test strategies are created, the engineer utilizing this methodology for design evaluation will be required to assess whether the previous qualifications considered a similar installed environment for the equipment and associated lightning protection. For the case studies, there is equipment that may have multiple suppliers which have not been included in the tables in Appendix C and Appendix D since the demonstration of the processes supporting the methodology is the main goal of the case studies and including that additional detail would not add significant value to the case studies. Thus the additional details regarding similar equipment from several different suppliers will not add to the learning intended. In this respect, some of the assessments require retrospective investigations. This may result in successful elimination of some planned equipment lightning protection installations that may not perform well over time and result in a revision to the certification basis in the process.

Equipment qualified by multi-airplane service history is noted in the Appendix C and Appendix D tables by the Qualification Method, “A/P Service History”. The service history rationale was given above for the ADF Active Antennas from two independent equipment suppliers. Equipment qualified by analysis used a similarity assessment such as the equipment panels and flight deck panels (panel numbers retained). This equipment consists of seven X panels, the Y panel, and the Z panel (Panel numbers retained), all of which were changed only by the installation of the new Universal Master Caution (UMC) card. These panel housings remain unchanged from the first installation of the Aircraft A and are similar to the X and Y panel housings (Panel numbers retained). The X and Y were the panels chosen to be tested since these two pieces of equipment were being changed by installing additional new cards besides the UMC.

Equipment qualified by test requires a full qualification test be performed for the aircraft in the case studies. Included in the list are: (Equipment names retained).

As can be determined by the various techniques used to establish the way forward to certification, testing of equipment is not always used to qualify equipment. In case of lightning protection, certain equipment protection schemes may have been used on past designs for protecting wiring and electronic equipment that are selected for the new designed aircraft without a reaffirmation from a qualification test. In that case, components that are subjected to the assessment sheets must not be limited to only those equipment designs that go through a qualification test. This intelligence should be used to ensure that no component performance is “assumed” to be adequate for the life of the airplane due to the long history of that particular components application on other aircraft designs.

5.13 Results of Case Studies

The analysis sheets work well to understand the potential performance of a lightning protection component. To subsidize the analysis, one must be able to identify the designed lightning current path in order to perform an evaluation of the entire lightning protection solution. Results of the assessments will be generated and distributed to the design team leaders that are affected. A cross analysis of the assessment findings may be necessary when specific findings are recommending a change in the design. It is important to understand from the case studies that many designs are adopted from past aircraft programs. This is sometimes the right way forward as it may result in lower costs to develop the new aircraft. However, as the case studies demonstrate, past designs may not be robust enough to meet the new aircraft performance expectations defined at the beginning of the aircraft development program. For this reason, it has been demonstrated in the case studies that accumulation of design goals for lightning protection performance is critical to achieving the expected optimized design outcome.

During development of the case studies, several findings surfaced that caused changes to the format of the assessment implementation. Some of the improvements made to the case studies are listed as follows:

1. Assessment sheets revised to include maintenance recommendations
2. Inclusion of a detailed environmental design guide into the process
3. Added dates and sign-off blocks to the assessment sheets
4. Added certification plan data and relevant details regarding lightning protection
5. Included a Pareto chart to clarify different effects lightning has on aircraft
6. Incorporated a detailed table of regulations related to lightning protection design and how the regulation affect the design decisions
7. Enhanced the discussion regarding system safety and regulations associated with electromagnetic protection design assurance levels
8. Included SAE design criteria from SAE Aerospace Recommended Practices (ARP)
9. Included practice for relocation for protection components in cases where the assessment concludes an option for the protection location
10. Included additional information relevant to the OEM Design Manual for lightning protection design. Identified opportunity to improve the manual
11. Included both composite materials and metallic materials in the case studies
12. Included information on evolutionary lightning protection from past early aircraft designs (aircraft types retained).
13. Incorporated concepts from the aircraft design handbooks titled, “Aircraft Design: A Conceptual Approach” [5.7], and a text book titled, “The Aerospace Engineers Handbook of Lightning Protection” and an aircraft design text titled, “Introduction to Aircraft Design” by J.P Fielding [5.6].
14. Lightning Strike Zones reference was added to the assessment sheets to provide a frame-work for the analysis
15. Determined that certification levels should be referenced in the analysis sheets.

From the results of the analysis sheets that demonstrate one way to implement the methodology, the conclusions for each lightning strike protection design have proven to be useful in improving the design. The analysis sheet approach is adequate to demonstrate the integration of design issues presented in the methodology. In one case an improved design was determined that would be implemented on the aircraft before the aircraft was type certified. A cross examination of the results could be performed by assembling the analysis sheets for each design within a single team and initiating a system for the review by system design team leaders. This practice of developing integrated system design methodologies has been successful on many aircraft and aerospace vehicle design projects. The results of these case studies however, bring an integration solution to the design of lightning protection that result in better performing products and optimized designs when considering the installed threats.

5.14 Limitations of Case Studies

One of the major limitations of the case studies is the accessibility of the data required for proving the methodology. Data gathering for these case studies can be tedious if the data sought is not expected to be used in the fashion presented by the case studies. In real-life application of this methodology, the aircraft design team would establish a data-gathering plan and capability to ensure that the design evaluations are performed in a timely and efficient manner. The nature of this limitation is likely a direct correlation to an aircraft that is already designed.

Another limitation of the case studies is the proprietary nature of the data used in the analysis. Certain data from aircraft derivative development programs may rely on past designs that did not collect the required data in a fashion that is convenient to performing the proposed methodology. Data exchange may also be challenging if proper proprietary data agreements are not in place. In order to perform the case studies, a contract between the university and the aircraft manufacturer was implemented. This limitation should not be present if the aircraft design was created and developed by the same manufacturer. In cases where the designs are outsourced to partners of suppliers, agreements between the manufacturer and partners like the one between the university and aircraft manufacturer to support this body of work is necessary. This is especially true for the mining of past experience with certain specific designs that adds to the analysis within the work sheets of each case study. This creates a sometimes awkward reference system within the case studies to hide the source of the information or the aircraft types referred to in the certification similarity arguments.

The case studies demonstrate the need for historical information and service experience gathered in a single convenient database. With the industry trends towards partnerships between corporations, the access to specific customer experience regarding lightning protection components is limited to the ability of the integrating company to collect the required experience and make it easily available to its partner supplier base. For instance, the specific experience with composite structure interfacing with lightning protection that conducts lightning currents may not be present within the composite structure supplier support department. This type of data can be generated only in cases where the prime contracting company shares support responsibility. From the business perspective, the supplier may only require that serious issues with the components in question be brought to the attention of the supplier support engineering department. At the same time, the design of certain protection components such as the metallic lightning protection frames on the rudder tip may be managed closely by the prime integrator of designs and checked against the criteria presented in the assessment sheets.

As for the case studies presented in this thesis, the selection of case study designs exercised several different protection components types offering diversity in the case studies that proves the approach can work with structural, systems and interconnecting protection designs. Additional analyses of similar types of lightning protections were not included to eliminate redundancies in the case studies.

Another limitation of the case studies was the use of data from an already designed and produced aircraft. Though the case studies evaluated certification documentation, data from tests performed on the aircraft at the time of the design development, and similarities of past designs even back to aircraft built in the 1960s, the case studies proved that this limitation would not be a hindrance to exercising the methodology proposed by the author. On the contrary, the use of the methodology during an aircraft development program offers more freedom to revise assumptions and designs based on the findings of the associated assessment sheets.

A final limitation is the ability to demonstrate through a series of case studies that the application of this methodology to new and novel designs is valid. Since the case studies were performed on an aircraft developed as a derivative of an earlier design in 1997, advances in materials, equipment integration and new lightning protection techniques may bring certain unknown problems in performing the assessments. In general, the flexibility built into the design assessment sheets provide for expansion of this methodology to include evaluations of new or novel designs.

5.15 Lessons Learned and Knowledge Produced

As the methodology was exercised in several case studies contained within this section of the thesis, it was determined that the integration for this new design approach was very important. Evidence was presented within the case studies that showed a practice of using old design approaches to lightning protection since no performance issues are known at the time of the design decision. Using past designs has the advantage of reducing costs associated with the battery of tests required when a new system is certified. The issue with the approach to adopt past designs discovered in the case studies is the lack of associated investigations into the continued airworthiness of the parts that have been previously certified. The case studies demonstrated that an assessment for continued airworthiness can be applied for parts that implement new designs and parts that use previous designs. For lightning protection components that are certified by similarity, the retesting of the parts is not necessary in order to complete the design assessments proposed by the case studies. These previously used designs can use real-world experience with the continued airworthiness in place of certification testing to help properly assess the components. This was actually demonstrated by the case studies since the components within the studies have already been certified to be incorporated into the aircraft used as an example in the case studies.

The case studies investigated the possibility that data would be available to perform a wide-spread evaluation of the lightning protection continued airworthiness on an aircraft development program. Within the case studies, it was determined through practical application that new technologies can also be evaluated with the methodology. The reason that the methodology easily addresses new technology is in the design of the assessment sheets and the inclusion of an electrical bond path definition for each protection component. Once a bond path is determined and agreed within the design process, then new technologies can be assessed by determining the main features of the technology that allow for current to flow during a lightning strike event. This was proven by the examination of a composite rudder structure where a metallic picture frame is used to reduce damage due to lightning strike by directing the current along the more conductive metallic strips. Without the metallic strips the higher resistance composite structure will cause the current to increase and result in more severe damage to the attached location on the rudder. The methodology was exercised by examining the installation features of the metallic strip against the expected environmental threats present during flight and a life-long operation of the aircraft with this particular installation in place. The methodology is not intended to determine if the installed protection performs its function, but rather the methodology is in place to ensure that the lightning protection continues to perform its function over a long period of time. For this analysis, the purpose of the installed lightning protection must be understood and the detailed description of the intended operation of the protection during the lightning strike is also necessary.

Another lesson learned comes from the nature of performing the analysis after the design is in place versus performing the analysis during the design development phase of the aircraft development project. The methodology is perfectly situated to perform analysis both after the design is in place and during the design development process. The revelation however, in performing the case studies on an aircraft design that is already in service was the opportunity to involve the examinations within the actual design development process as a way to improve the design at the time of its creation. By performing the analysis after the design is fixed, the opportunity for improvements to the design is diminished. Findings for recommendations of improvements that can be made may be compromised by the expense of replacing all the applicable protection components after the aircraft is in service. To assist with this situation, it was discovered that maintenance recommendations should also be part of the examination process contained in the methodology. A change to the assessment sheets was made to address this concern. Another benefit of this methodology during the design process is the potential that the analysis may find a better way to transfer the current during a lightning strike event and offer a more robust solution to the protection design determined by both evaluations of test results and of service experience associated with previous aircraft configurations.

The nature of this methodology to address long term performance issues generated a discovery of the importance of design goals. In lightning protection certification, design goals are established by industry standards that ensure the design meets the intended threat while performing its intended function of passing the current safely through the aircraft without system or fight upsets. The nature of these specifications is not to determine performance margin associated with the long term survivability of the protection components. Use of this methodology brought attention to the importance of meeting design goals not just for performance, but also for the long term availability of the lightning protection. Incorporation of the methodology within the design process enhances the lightning protection designs.

Another discovery as a result of the case studies is the need within a design process to integrate knowledge and purpose. For lightning direct effects protection, use of metallic strips on the outside of an aircraft structure can affect the aerodynamic performance of the aircraft. Transition of the metal to the composite should be smooth while also providing protection from the potential for the metal to corrode. Composite fiber structure and aluminum metallic strips are not compatible materials in the presence of moisture. Corrosion of the metal can reduce the current carrying performance of the metal. Also, holes drilled into the composite structure for the purpose of mounting the metal strip can provide a means for moisture to enter the composite structure and cause the composite material to delaminate. This single environmental threat may be reduced by addition of sealants or primers called corrosion inhibiting compounds. It is important however to compare the need for a good current path with the requirement to avoid the negative effects of moisture since some corrosion inhibiting techniques can reduce the electrically conductive nature of the design. This demonstrated the need for engineers and designers within different disciplines to collaborate the design alternatives across the systems and structures boundaries. A central organization may be best suited to lead this design function to remove any potential adoption of lightning designs based on familiarity or affinity to certain design approaches. Since the design solutions of some goals may actually be counterproductive to other design solutions in the composite structure and metallic strip example, it was discovered that use of this methodology will increase awareness of the importance for design integrations to be performed across disciplines. This is also highlighted through experience with designing aircraft across a multiple supplier base. Aircraft development programs that include large scale partnerships must have a robust integration solution for the design development in order for this methodology to be performed with ease.

The use of the assessment sheets to implement the methodology demonstrated the importance of leveraging service experience. In research of the certification process, it was discovered that systems that have been certified on past aircraft designs may not be evaluated for certification since the use of similarity may regard the configuration as “already certified” resulting in lowering the cost of a potential re-certification for the same design. The discovery here was that previously certified systems may have performance issues that could be improved by application of this methodology but would not otherwise be evaluated if the design process selects to incorporate the same design based on the cost of re-certification. Within the case studies, it was discovered that the very early aircraft designed in the 1960s was referenced within the certification documentation to eliminate the need to pass the design through the regulatory evaluation process and cause further expense to the program. The interesting result however, was the incorporation of bond jumpers that are known to degrade in service but have been certified for use on a past aircraft design. Since this methodology can evaluate already existing designs as well as newly developed designs, it offers the flexibility to evaluate these bond jumpers without having to pass the design through a re-certification process and then allow for the informed decision to incorporate the bond jumpers used on past aircrafts or revise the design and accept the re-certification as an improvement provides more benefit than avoiding the certification costs for a new design. Designs that are adopted from past certification programs may be acceptable for certification i.e. low risk, but may not be examined for potential optimization unless a technique is used like the one presented in this body of work. Certification strategies that adopt past designs to ease in the expense and developmental costs may not be the best way to determine an appropriate design alternative.

The use of analysis work sheets proved useful in deploying the methodology. As the case studies were conducted, it was determined that the analysis sheets should be revised to include additional features of the analysis that were not known at the time they were originally created. The flexibility of the design analysis sheets was discovered to be very useful in adopting additional needed steps such as the inclusion of the environmental threat tables. These tables were created to ensure that the environmental threat assessments within the analysis would be done in a similar manner so as to provide a design methodology that is transparent to the individual performing the analysis. Further development of the analysis sheets is expected as the concept is improved and the analysis process is further developed.

Repeatability of the analysis was demonstrated by inclusion of four unique protection designs across both direct and indirect effects protection components. The flexibility of performing the analysis on both direct lightning effects and indirect lightning effects was also proven through actual case studies of both protection type designs. This successful analysis is a good indication that such a design methodology can be applied across different components and is a repeatable and robust process.

5.16 Conclusion

The case studies proved the practicality of the proposed methodology. In the earlier part of the case studies development, an assessment sheet was created to exercise the methodology. Several changes were made to the assessment sheets to improve the process as the case studies progressed. The following is a list of the changes that were made to improve the assessment process and apply real-world requirements sourced from the case studies data.

Assessment Sheet Section Changes Resulting from Research

Section 1 - Lightning/HIRF Protection Component Data

- Added an assessment sheet number to distinguish each assessment sheet. The numbering system incorporated a code in the numbering system that identified the particular type of lightning protection and a serial number.
    - Structure lightning protection - STR001, STR002 etc.
    - Fuel ignition lightning protection – FUL001, FUL002 etc.
    - System lightning protection – SYS001, SYS002, etc.
    - Antenna lightning protection – ANT001, ANT002 etc.
- Added the engineers name performing the assessment
- Added the lightning Zone in which the protection is installed, e.g. Zone 1, Zone 2, or Zone 3
- Added the date in which the assessment was performed. This is to ensure that any revisions to the assessment are not confused with earlier versions.

Section 2 - Component Description

- Added system criticality.

Section 3 - Component Purpose and Operational Theory

- No Change

Section 4 - Component Schematic and Installation Details

- Added lightning electrical current path and interfacing component description

Section 5 - Installation Environmental Threats

- Added a description of the installed environment
- Added Flammable leakage zone description and protection information
- Added an environmental threats rating table
- Added environmental threat severity for each threat
- Added installation resistance to the environmental threats

Section 6 - Assessment of Critical Characteristics in the Installed Environment

- No change

Section 7 - Test Plan Input

- No change

Section 8 - Test Data Results

- Added qualification test pan steps

Section 9 - Report from Test Engineer Regarding on Continued Airworthiness

- Added conclusion section for assessment of the item

Section 10 - Design Revision Request

- No change

Section 11 - Revision accepted by Program

- No change

Section 12 - Description of Final Optimized Design

- Added an “action taken” section
- Added Approval signature block

The proposed analysis process used in the validation section of this thesis was revised by experience gained in the case studies. Additional drawings information and details on the certification basis for the lightning protection component are also included in the case studies but were not included in the validation section of the thesis. Improvements were made to the process by including more scientific examination of the lightning protection components such as the galvanic table to be used in determining whether appropriate steps are taken when materials are not compatible in the presence of moisture. The case studies also demonstrated that some designs are not optimal at the time once they are approved if they are not subjected to an analysis such as the one proposed within this work. The designs that were examined were found to have some shortcomings such as the example of the tin plated copper bond wire in the harsh environments. The case studies included two different aircraft crash reports due to lightning. In one case, the lightning strike was not well managed by the installed lightning ground paths die to missing ground jumpers in the horizontal tail assembly. These missing ground wires resulted in the lightning moving down an alternative path that was not designed to safely pass the high current generated by a lightning strike. With the ground wires missing, the alternate path included some hinges in the horizontal stabilizer flight controls components that were subsequently welded together and rendered ineffective in controlling the safe landing of the aircraft. The case studies demonstrated that installations such as the bond jumpers noted in the referenced crash investigation would have been recognized for the significance to the entire design and potentially, could have been maintained or the design revised due to possible failure to pass the current through these bond jumpers caused an aircraft incident.

Through the development of the case studies, elements were explored that caused better understanding and improvements to the use of the methodology such as:

1. Aircraft environmental threats
2. Incorporation of corrosion discussion, a galvanic table and explanation of the association between galvanic deterioration and continued availability of good electrical contact.
3. The significance of a development program and development program phases
4. Criteria demonstrating safety on aircraft systems installations
5. The importance of test data and relationship between testing and design improvements as an iterative process
6. Impacts of previous certification retaining old designs and inhibiting an improvement to the new designs
7. Classification of analysis and different protection schemes
8. Examination of the certification process that leads to design creation
9. Detailed explanations of different lightning protection designs and associated key features of those designs.
10. How lightning affects operations including an examination of a typical lightning strike inspection to assist in understanding what is considered “at risk” for damage from lightning strike.
11. Exploration of sealants, the process for sealing lightning protective interfaces and associated design issues when improper sealant applications are present
12. A summary of two different crash investigations and subsequent recommendations provided by the regulatory agencies that highlight issues that can be caused by either poor designs or poor evaluations of the designs at the time of the final approved protection system implementations
13. Detailed information on lightning zones, the process for determining lightning zones and the associated electrical threats presented within each zone. This exercise resulted in revision to the assessment sheets to include a reference in which lightning zone the components on the assessment sheets are installed. The determination of lightning zones is also an iterative process that may result in design changes as each design improvement is completed. These iterations will also derive the design assessment revision and resulting assessment sheet modifications.
14. Details associated with connector designs
15. Elements of a safety analysis and selection of lightning protection designs
16. Maintenance program development and support for better performing designs resulting from the design assessment methodology
17. Lightning protection certification and the need to evaluate some designs even if they have been previously certified and included within the new design to be certified by similarity.
18. Multiple case studies were explored that covered a variety of lightning protection types and resulted in a wider understanding of the value an assessment can provide to the final designs across multiple protection types

The following examples demonstrate how the case studies evolved and list examples of the benefits that were generated by performing the case studies.

- In the earliest version of this chapter, a description of interacting aircraft lightning protection design processes. The case studies started with very little data or literature searches to provide the data necessary for the exercise. Further development created multiple paths through the design process and descriptions of details associated with the different paths through design phases. Also included in the early part of the case studies were some rudimentary descriptions of lightning protection designs features.
- Several months later in the case studies more detailed evaluations of regulatory guidelines were added to the case studies that represented many more literature searches. Additional information of federal regulations and industry standards were described. Many more details gathered from literature search for protection schemes and components including antenna issues, information on degradation of installations, and known design shortcomings.
- As the case studies were developed and continuous reviews with the PhD supervisor were conducted, many comments modified the case studies with regard to scope, addition of test cases, and selection of cases with composite and metallic features in order to demonstrate potential real-world differences in materials. Also added to the case studies through guidance from the PhD supervisor were discussions on improving an existing design vs. evaluation of new designs. Additional information on how to deal with revolutionary designs was also added to the case studies. At this point, it was determined that the certification process has an impact on the design process. As a result, it was necessary to investigate and describe the certification process, especially its quirks regarding the use of similarity as a way to determine design implementation. More research was conducted at that time to expand on the certification and development interactions. This required additional literature searches in aircraft design handbooks such as the AIAA "Aircraft Design: A Conceptual Approach", book and, "The Aerospace Engineers Handbook of Lightning Protection" design book. The results of the literature search on this subject introduced the concept of revolutionary designs and further development of the meaning of design stages (Conceptual, Preliminary, and Detailed). The differences between the stages and application of the proposed design methodology generated a detailed discussion with the PhD supervisor and generated further understanding of the aircraft design processes. The outcome was the examination and incorporation of details which helped define how the methodology will fit into a typical aircraft development program.
- Further development of the case studies expanded on the aircraft design process and the subject of incorporating continued airworthiness into the process. This generated research on aircraft design phases and discovered the importance of early goals for lightning protection.
- In order to establish a baseline for the case studies, assumptions were included in the description of the case studies. The subject of known lightning phenomenon and lightning impacts on aircraft operations was also expanded through literature searches and include in the case studies. Part of this additional information included more specifics on the attachment of lightning to the aircraft

in the case studies, probabilities of lightning strike locations from literature searches, and lightning zone design processes and definitions. At this point in the case studies development, aircraft lightning protection was listed for both direct and indirect lightning protection. This list is instrumental in determining the scope for practical application of the methodology. Lightning protection drawings also were included in the case studies and more detailed research of lightning protection components was performed resulting in more data that was subsequently included the studies.

- The use of an assessment sheet was also introduced by the case studies. The early version of the validation did not include an assessment sheet concept, though the idea of including the continued airworthiness review remained central to the assessment. Analysis sheets were developed and revised several times over the course of the case studies exercises. Additions and revisions to the assessment sheets are described at the beginning of the case studies conclusion section. The design of the assessment sheets was discussed with the supervisor to ensure that a reasonable representation of the intent of the methodology could be demonstrated.
- Continuing literature searches increased the amount of data included in the case studies. These literature searches created more details of specific lightning protection designs on the aircraft in the case studies and descriptions of the protection components that were added to the case studies. At this stage, details regarding the aircraft environment, aircraft environmental threats data, and associated details of the wire installations criteria in vibration, temperature and moisture-prone areas were determined. An explanation of the lightning threat to aircraft systems through faradays laws was created and a discussion surrounding the effects of lightning current on transport elements such as hydraulic tubes was also incorporated into the case studies.
- More examples of different electrical bond paths were provided as the case studies developed with detailed explanations regarding the varied sources of information on an aircraft development program. The source of continued airworthiness requirements was explored. This led to an observation that there may not be a central location in the design team for coordinating and consolidating requirements. A centralized design function would help ensure the designs meet the requirements from the multiple design perspectives.
- In earlier development of the case studies, the inclusion of maintenance requirements was not considered germane to the methodology. After discussions on this issue with the supervising professor, the case studies were modified to incorporate potential maintenance as an alternative to redesign of a lightning protection components where findings in the assessment may have recommended redesign as an alternative. This new understanding resulted in revised assessment sheets and will also impart a revision to the methodology.
- It was also determined that instructions for inspection of lightning protection after a lightning strike attachment to an aircraft would provide a good understanding of the things within the design that most aircraft manufacturers consider important. For this, current maintenance manuals were explored. Research into the maintenance manual and across several different aircraft manuals including the structural repair manual provided information that was

included in the case studies to highlight the general principles associated with aircraft lightning protection inspections. For lightning protection designers, this knowledge greatly enhances understanding continued airworthiness issues associated with potential damage to the aircraft after a lightning strike.

- At mid-stage in the case studies development, two aircraft crash reports from legitimate regulatory investigations that were found to be due to lightning strike events were included as part of the case studies. These investigations led to understanding not only how lightning can affect the continued safe flight and landing of an aircraft, but also provide information on the importance of maintaining lightning protection as the aircraft ages. In one case the evidence of missing or improperly installed bond jumpers (earthing wires) was found to be a cause of the aircraft loss of stability after it was struck by lightning. This can be also correlated to understanding the effects of poor designs. The conclusion was that continued airworthiness of lightning protection is a key design specialty and if done poorly, can have hazardous effects on the aircraft operation and impact the safety of passengers and flight crews. In the case of one of the crashes, passengers and flight crew were harmed by a hard landing due to reduced controllability of the aircraft after the lightning strike causing subsequent collapse of the landing gear upon touch down. In the other case, lightning was suspected to have caused a complete electrical failure. Revision to the aircraft flight manual has been recommended to include instructions to thoroughly inspect the aircraft after lightning strike when loss of electrical power or interrupted power results from the strike. All nineteen passengers and two crew members were killed in this crash.
- Further development of the case studies investigated the importance of electrical bonding within aircraft designs. Literature searches resulted in discovery of an electrical bonding design guide developed by the OEM that was in need of update to bring the bonding practices developed for the new aircraft design processes into the forefront. Reference to this design guide was included in the case studies. The aircraft that was the subject of the case studies was not designed to the new standards found in this bonding and grounding design guide. The importance of an electrical earthing design guide was highlighted and inclusion of the design guide into applications of the methodology resulted. For early aircraft designs, it was thought that sealant may not be necessary within electrical bond joints, especially in applications where a bond jumper or earthing wire was attached to a piece of equipment that may be removed for maintenance or overhaul.
- Bond paths for electrical installations were described in detail. During a lightning strike event, lightning current travels along the structure of the aircraft. Wire installations will also carry current to the attached equipment. It was determined in the case studies that wire installations rely on brackets attachment to structure, equipment attachment to aircraft structure, installed shield wires within the wire looms and bond jumpers that may attach between the brackets and structure or the equipment and structure. For each of these interfaces, a specific impedance is required as part of the design to ensure that voltages generated by the lightning current are kept to acceptable levels. For an aircraft development program, the expected “standoff” voltage that any control

equipment would experience at the junction from outside the equipment to the internal equipment control electronics is established by the design team. Working with this requirement, designers for aircraft equipment establish appropriate electrical bonding schemes to ensure that the required voltages are within the specified levels. These bonding schemes are important to remain effective throughout the life of the aircraft. The conclusion from the case studies is that more specialize and concentrated effort to provide design solutions for electrical bonds that will perform as intended over the life of the aircraft would provide is benefit to an aircraft design team.

- Through research within the case studies, it was discovered that sealant applications are an important part of lightning protection continued airworthiness. Sealants may be applied after the terminal joint is assembled or as part of the assembly process in-between the fastener parts (washers, nuts, terminals etc.). When a sealant is applied at the gaps between two interfacing parts after an electrical joint is assembled, this is called a fillet seal. Fillet seals have been identified to increase the possibility of trapping moisture in cases where the installation is outside the pressure vessel. For applications inside the pressure vessel, this bonding technique may be perfectly acceptable to meet continued airworthiness expectations. The degradation of a fillet seal outside the pressure vessel is brought about by imperfect fillet seal application that may include a small unseen void in the sealant. In this case, the void would act like a siphon when the aircraft is cycled from standard ground atmosphere to a much greater altitude pressures. This would cause moisture to be drawn in and out of the joint causing potential corrosion in cases where the materials in the fastener "stack-up" do not demonstrate galvanic compatibility. Understanding appropriate applications of sealants, appropriate types of sealants and the relationship to the continued airworthiness of the installation was achieved through exploration of information surrounding this topic. As a result of this learning, the analysis sheets that drive the assessments for continued airworthiness were revised to include the sealant application and type. In a similar manner, cleaning methods associated with preparation of electrical bonding installations were explored and included within the analysis. Specific electrical bonding information regarding the aircraft in the case studies was acquired through literature search and is included within the case studies.
- The concept of primary structure lightning strike protection and secondary structure lightning strike protection was examined and its impact on the case studies as a way to organize the design process. The application of the case studies concludes that structural installations where lightning current is expected to pass through the structure must be examined by the lightning protection continued airworthiness team to ensure the dual purpose of structural integrity and lightning protection function are both met by the structural design.
- The concept of systems equipment criticality was explored. The difference between the criticality as determined by the FAR 25.1309 safety analysis and the safety determinations through the Design Assurance Level (DAL) process associated with AC20-136 guidance were clarified. Findings were provided that demonstrated how a system considered non-critical by the safety analysis performed under guidance from FAR/JAR 25.1309 could be elevated to a

hazardous or catastrophic level failure when evaluated by the lightning in-direct effects process in AC20-136. This observation emphasized the need for understanding the electromagnetic perspective for lightning protection safety determination and also highlights that direct application of the systems safety analysis results may cause an incorrect classification of lightning protection components. This incorrect determination of the lightning protection significance could drive incorrect protection applications. The subject of new or significantly modified systems was explained along with its potential impact to the proposed methodology. Safety assessments for 25.1309 failure hazard assessments may require additional assessment and integration from the Design Assurance Level (DAL) analysis to identify lightning protection component significance.

- It was discovered that the lightning certification process has a large impact on the lightning protection design development. Further research about the certification process and its impact on the methodology was included in the case studies. In cases where components were certified on past designs and previous aircraft development programs, additional design assessment may not be performed by the design community. This approach to adopt early design solutions based on past certification on previous aircraft could lead to sub-optimal designs and perpetuate design features into new aircraft development programs that could be improved for continued airworthiness if the methodology is applied. The case studies concluded that the methodology could be used for new and reconfigured or derivative aircraft development programs.
- Research done within the case studies identified a report by the National Institute of Aviation Research that evaluated aircraft with and aircraft without lightning protection. The studies determined that aircraft that are fully protected from lightning adverse effects had a significantly lower percentage of electrical failures. This discovery validates the proposition that the demonstrated methodology would bring a significant value to the aircraft design process.
- Lightning protection maintenance can be optimized with the use of the design assessment methodology. Changes to designs may be recommended and subsequently evaluated for practicality by use of a feedback system added to the early version of the methodology. This feedback loop was proposed after discussions with the supervising professor and revised in the methodology definition prior to completion of the case studies.
- The association of design details contained in the case studies and specific lightning protection component installation information yielded some conclusions within the assessment sheets that require further design engineering guidance. This is a good indicator that the design process would benefit from the assessment techniques exercised by the case studies. Inserting more information from service experience can improve the proposed methodology.
- Incorporation of a materials chart describing the galvanic characteristics of differing metals may be an improvement to the methodology.
- A revision of the methodology to directly tie the environmental threats design criteria and the approved parts list process into the methodology and assessment sheets should be explored more deeply. Indications from the case studies pointed to processes internal to design communities for selecting

acceptable components within t certain operating environments that may perform well initially, but not over time.

- Aircraft lightning zones identify the severity of the electrical current and the probability of a lightning strike in that aircraft location. The assessment model for lightning protection components may benefit from including the zone in the assessment sheets. These sheets were revised during the case studies exercise to accommodate this feature. Further exploration of the significance of lightning strike zones to the lightning strike protection may be beneficial.
- The case studies demonstrated that both direct and indirect lightning strike threats can be practically addressed by the methodology.
- Information gathering of aircraft components for the case studies was very tedious and demonstrated that an integrated process for including the lightning protection design continued airworthiness into the development phase of an aircraft design program would be more effective.
- Some of the required details for the assessment sheets are contained in the installation and parts list drawings on several sheets. The case studies demonstrated that this information is not collected in a single location. Further evidence on the importance of integration within the design project was gathered by exercising the effort to gather different design details across multiple drawings. The assessment sheet used in the case studies assisted with the effort of integrating information and design details.
- Improvement to the methodology can be achieved with further development on new design approaches. The design assessments contained in the case studies were performed to determine if a design is expected to last the life of the aircraft given certain inputs from multiple sources. Several sources of information will require integration from individual groups such as electrical designers, fuel ignition prevention designers, wiring designers, material sciences experts, composites experts.
- The methodology exercised in the case studies would result in benefit if it were developed further to increase the integration during the design development phase. The practical application of the analysis through use of the assessment sheets in the case studies can be developed further to include a design assessment committee rather than just an assessment sheet completion. This would have the benefit of tying the design improvement to the design assessment committee. The assessment sheets can identify problems, but do not include the potential solutions other than a simple recommendation. Further work on this concept is needed.
- The case studies identified the association of electrical bonding and grounding knowledge to lightning protection continued airworthiness. Since the electromagnetic compatibilities and electrical bonding and grounding skills are departmentalized, the assessment sheets provided evidence that cross examination between these two skill sets benefit the final design outcome.
- The model aircraft in this case studies is not highly integrated. For highly integrated aircraft, the importance of designing the continued airworthiness into the lightning protection expands to include many more systems. The analysis sheets are designed to address this more highly integrated design and assist with

the cross-organizational support that is necessary to succeed at designing highly integrated systems.

- The aircraft design process is iterative in nature. The use of the assessment sheets in the case studies demonstrated that feedback from design assessments is important especially when a system is found to be inadequate for the life of the aircraft. An example of this was included in the case where a connector design was found to be inadequate for the application outside the pressure vessel and feedback to the design community was generated by the assessment.
- The case studies demonstrated that the use of a failure hazard assessment is not enough to address the lightning protection design robustness over the life of the aircraft. The concept of design assurance levels was introduced within the case studies that assisted with the necessary categorizing of lightning protection systems. An entire section of the case studies was dedicated to the concept of safety and the different processes associate with design assurance where the effects of these processes differentiates the input to the methodology.
- Later in the development of the case studies, the concept of maintenance program development and impact was introduced as part of the design development. This is not a normal industry standard approach as the maintenance program is generally determined after the designs have been completed. This early incorporation of the maintenance program requirements incorporates more advantage to the design methodology as it can further optimize the design not just for the continued airworthiness but also for the mitigation of maintenance costs later in the life of the aircraft.
- The case studies demonstrated that the earlier design approach used to develop the aircraft under study did not incorporate the best design solutions. This can be correlated to the lack of an integrated design process such as the one hypothesized within these works and demonstrated by the case studies.
- After review of the EMC test reports generated at the time of the aircraft examined in this body of work, it was noted that the continued airworthiness of the EMC protection under test was not included as a category within the report structure. This issue would result in fewer components reviewed with the assessment sheets. However, if assessment sheets were used at the time the aircraft was in its design phase, this issue would have surfaced through the assessment methodology and resolved by a proper disposition.
- As a benefit to of the assessment sheets identified by the case studies, the requirement to test the component resistance at time of installation may be helpful to add to the assessment sheet. These specific electrical bonds are important to be installed properly, but through findings from the case studies, a systematic approach at the time of the aircraft development did not include the examination of the installation process or design to ensure that the continued airworthiness of the installation is maintained.
- During development of the case studies, the lightning protection continued airworthiness design handbook developed by the OEM was discovered. This handbook is out of date with today's design practices. Development and improvement to the manufacturers own internal design handbook would be a great improvement to assist the next design community on the next

development program to design the aircraft according to the best known practices for lightning protection continued airworthiness.

These findings and the new discoveries provided by the research listed above summarize the important outcome of the case studies. Overall, the case studies proved that the methodology could be applied to an aircraft design and also generates a positive outcome to the design.

Chapter 6 Lessons from the Case Studies and Revised Methodology

6.1 Methodology Success and Updates Made to the Methodology?

The methodology as applied to an aircraft development program worked very well in meeting the goal to optimize the lightning protection designs. The proposed methodology revises current aircraft design processes for creation of Lightning/HIRF protection designs. Supporting this design methodology revision is the integration with the newly adopted MSG-3 maintenance program development methodology. Adoption of the proposed aircraft design methodology as indicated by test through this body of work can result in more efficient Lightning/HIRF protection designs which require less scheduled maintenance. Cases where designs were assessed using the methodology provided design revision recommendations that were not known at the time the original design was created. This finding resulted in a better design and could also have improved the design when it was originally created. With the recommended changes made to the lightning protection designs coming from the use of the methodology, the resultant design would improve costly redesign later in the aircraft life while also eliminating the need for scheduled maintenance. Findings using the methodology include improved material compatibility for lightning protection components in long term applications. Since these material compatibilities are not evident when new, some designs may not find these compatibilities an issue at the beginning of the design process. The methodology takes care to identify design issues such as material incompatibility through careful and deliberate examinations of compatibility within the applied environments over long term utilization. In evaluating the nature of the methodology without consideration for the application to lightning protection, it was discovered that the methodology could be easily adapted to other disciplines. This has the potential to provide long term availability of certain specified performance criteria over the life of the aircraft in other design disciplines. In the case of lightning protection, this performance criterion is the continuous availability of an adequate low-resistance electrical bond path.

As the methodology was tested through application of the design data, the methodology was revised to improve and mature the concept. Through the data applications in the analysis sheets and literature search of design data, revisions to the methodology were determined appropriate. As these decisions were made while conducting the case studies, revisions were made to the methodology in Chapter 3. The original methodology was created with the idea that design data would be transitioned to the MSG-3 analysis process to determine appropriate scheduled maintenance. This is pointed out in Figure 6-1 below where it is noted that the methodology completes at the delivery of design data to MSG-3 analysis.

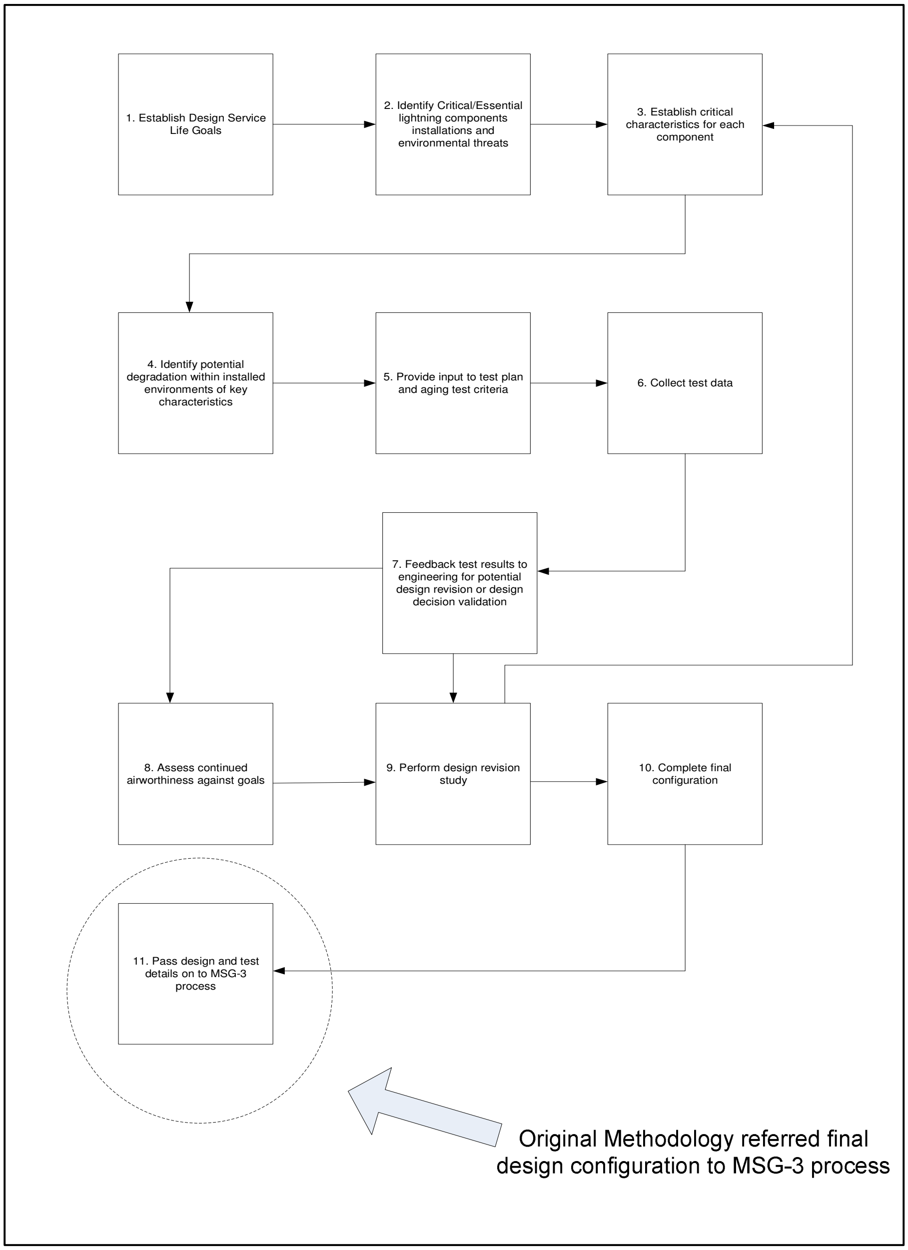


Figure 6-1-Original methodology proposed at beginning of the literature search

The methodology as it is presented in this final thesis documentation of the body of work is the culmination of several improvements. In the original methodology concept the MSG-3 analysis was stated as the final step in the methodology. Later versions shown in Figure 6-2 incorporated the concept of incorporating in-service and developmental flying performance data into the methodology in two locations. The first was to incorporate the in-service data into the design revision studies. The second input was to supply the same data into the MSG-3 maintenance program development process.

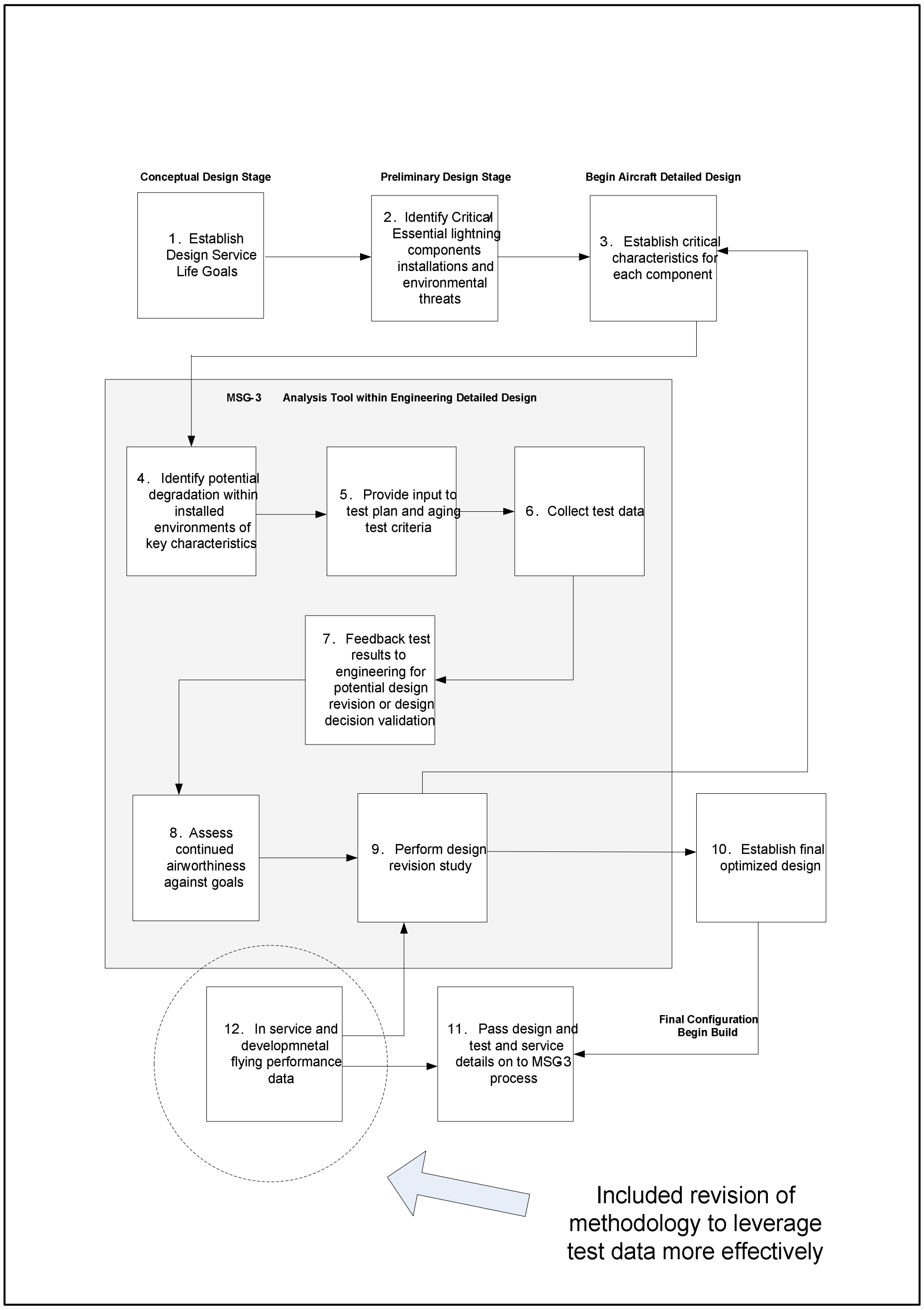


Figure 6-2 Revised methodology after validation and case studies completed

Review of progress in developing the case studies pointed out the importance of the path to certification since many certification documents were reviewed that impacted the case studies. As a result of this learning opportunity, the initial portion of the case studies chapter captured more details on the interacting aircraft lightning protection design processes. A single graphic of the participating engineering organizations was developed and included in the case studies, which was used to explain the potential unique paths to certification that exist at the time of an aircraft development program. Further development of the case studies then generated multiple paths through certification in an iterative manner. Descriptions of the details associated with the different paths through design translated into different inputs to the case studies which translated into a more robust methodology exercise. This exploration into the literature also provided details on some of the lightning protection designs features that would be included in the methodology exercise. This demonstrated the need for the engineering community that leads the exercising of this methodology to ensure that they are closely associated with the certification plans in order to identify the necessary design details to conduct the continued airworthiness design evaluation.

Another area where knowledge was gained in this exercise that has an impact on the methodology design was the inclusion of the Design Assurance Levels into the equipment criticality discussion. It was discovered that “system” criticality determined through the FAR/JAR 25.1309 process is the starting point for determining lightning protection criticality. A derived criticality for lightning protection is determined by understanding both the system criticality and the individual component criticality as determined by the electromagnetic compatibility evaluation of lightning protection electrical wiring components. The literature search performed as part of the case studies allowed for the discovery of these two differently derived criticalities to converge under one determination for the purpose of the lightning protection evaluations. The methodology may require further development in this area to include involvement in the lightning protection component electromagnetic Design Assurance Level determinations.

As the methodology was exercised through development of the case studies, system electrical ground paths were examined on several different lightning protection designs. As these electrical ground paths associated with wire looms and critical equipment were discovered, additional details were gathered from the design data sources where some of the sources were found to be certification documents. The confluence of the data gathering led to the understanding that these critical electrical ground paths require deeper examination during the early design phase of the aircraft development program and a more integrated view of the ground path determinations. This discovery also had an impact on the assessment forms. The first analysis sheet shown in Figure 6-3 design contained basic data and what was considered the most relevant information in one data sheet.

Engineering L/HIRF Protective Device Assessment Sheet
Protection Component: Radome Diverter Strip

1. Lightning/HIRF Protection Component Data

Name:
Part Number:
Manufacturer:
Design Service Life Goal:

2. Component description:

3. Component Purpose and Operational Theory:

4. Component Schematic and Installation Details:

5. Installation Environmental Threats:

6. Assessment of Critical Characteristics in the Installed Environment:

7. Test Plan Input:

8. Test Data Results:

9. Report from Test Engineer on Continued Airworthiness:
Test Engineer Name:
Report: (include significant findings and relevance to continued airworthiness)

10. Design Revision Request

11. Revision accepted by program

12. Description of final optimized design

Figure 6-3 First version of assessment sheet

During analysis, literature search and data gathering, it was noticed that the assessment sheets needed additional information to be more effective. The revised assessment sheet in Figure 6-4 provided for a more effective assessment. Graphic and schematic inputs were included to give them better usability and greater impact to the design operations. Inclusion of the lightning zone was determined necessary to connect the protection component more closely to the lightning threat as is done during the design of the protection components. Incorporation of the electrical bond path provided better highlights of the significant design features. The environmental threats were developed further to include a threat rating and whether the protection was within a flammable zone on the aircraft. A signature block was also added to provide the appropriate integration and authorization.

Section 1. Lightning/HIRF Protection Component Data	
Assessment Sheet Number	Serial Number of Component under assessment (STR=Structures, FUL=Fuel, SYS=Systems, ANT=Antenna)
Engineer Name:	Bill Boeing
Part Number:	P/N XXXX
Manufacturer:	Name of component manufacturer
Lightning Zone	Zone 1
Design Service Life Goal:	Design for life of aircraft. 20 years / 60,000 Flight Hours. No overhaul required.
Date:	November 12 2009

Section 2. Component Description
Describe the component that contains the lightning protection, the physical makeup of the component and the installation detail that allows the lightning protection to operate properly.

Section 3. Component Purpose and Operational Theory
Describe the function of the component that is protected by lightning. Provide how the function of the component is protected from the effects of lightning and describe the details associated with the lightning protection scheme.

Section 4. Component Schematic and Installation Details
Supply schematics, drawings, and illustrations of the parts that provide the electrical bond path and lightning protection. **Installation Details:** Describe the installation including mating surface materials, repair requirement details, physical characteristics of the installation and a description of the electrical bond path including the parts associated with each interface within the bond path. This should include the assembly requirements for each part that defines the bond path. **Bond Path Providing Protection:** 1. Part A detailed assembly description 2. Part B detailed assembly description 3. Part C detailed assembly description

Section 5. Installation Environmental Threats
Describe where the part is installed relative to the pressure vessel (inside, outside, protected or not protected from direct environmental threats). Describe each environmental threat and the significance of the threat to the established component life goals. **Description of installed environment:** Describe specific threat gradients, extremes and sustained threats. Provide a description of the long term exposures on the component. **Flammable Leakage Zone Description and Protection:** Describe whether location as flammable vapor or liquid threats and relation to the controlled lightning protection. **Ratings of environmental threats:**

Location: Nose Radome Exterior		
Threat Type	Rating of threat severity in this location (High, Medium, Low)	Installation resistance to degradation (High Medium, Low)
System Operating Fluids (oil, hydraulic fluid, Grease and Lubricants)	Low	High
Chemicals and Applied Fluids (cleaning fluids, fire retardants, de-icing, wing anti-ice fluids, liquid cooling)	Medium	High
Natural Occurring Fluids (condensation, precipitation, humidity, ice, rain, snow)	High	High
Temperature Exposure (swings in temperature, and extensive exposure to extreme high or low temperatures)	High	High
Vibration (low or high frequency vibration)	Medium	High
Fuel (Exposure to fuel)	N/A	High
Flammable Leakage Zone (Yes/No)	N/A	High

Location: Nose Radome Exterior		
Threat Type	Rating of threat severity in this location (High, Medium, Low)	Installation resistance to degradation (High Medium, Low)
System Operating Fluids (oil, hydraulic fluid, Grease and Lubricants)	Low	High
Chemicals and Applied Fluids (cleaning fluids, fire retardants, de-icing, wing anti-ice fluids, liquid cooling)	Medium	High
Natural Occurring Fluids (condensation, precipitation, humidity, ice, rain, snow)	High	High
Temperature Exposure (swings in temperature, and extensive exposure to extreme high or low temperatures)	High	High
Vibration (low or high frequency vibration)	Medium	High
Fuel (Exposure to fuel)	N/A	High
Flammable Leakage Zone (Yes/No)	N/A	High

Section 6. Assessment of Critical Characteristics in the Installed Environment	
Describe the continued airworthiness of associated components within the lightning protection designed bond path and affects on the protection caused be prolonged exposure to the environment. Identify potential failure modes due to degradation.	
Section 7. Test Plan Input	
Describe any environmental deterioration concerns determined by the examination of the part design, the installation techniques, and the environmental threats. Provide guidance for specific testing of conditions identified considering design goals.	
Section 8. Test Data Results	
Identify specific tests performed and relevance to the installed environmental threats. If tests are forgone due to similarity of past designs, identify testing for previously certified part and perform same examination. Describe the expected continued performance of the lightning protection in light of the testing results presented.	
Section 9. Report from Test Engineer Regarding Continued Airworthiness	
Test Engineer Name:	Tom Billing
Report: (include significant findings and relevance to continued airworthiness)	**Lightning strike diversion effectiveness**: Describe how the protection will continue to perform within it installed environment over the expected installation period. Also describe how the component that is protected will perform in light of the tests that have been conducted. Provide any known results of past component failures in service and associated reasons for the lighting protection failure. Comment on whether the proposed design along with both known in-service performance and laboratory test results will meet the expected installed performance goals.

Figure 6-4 Revised assessment sheet consisting of Nine Sections

The case studies exercise also identified that the assessment sheets can be improved from several vantage points listed in the following:

a. Include performance goals in each component assessment and also include the historical performance for each component.
b. Include any risks by correlating past performance to new applications on the new airplane development program within installed environments.
c. Include comments on environment differences such as applications of lightning protection components in dry and hot environments that may be proposed to be deployed into moist environments.
d. The correlation to the FAR 25.1309 systems safety analysis process could be created. This could also include the equipment Design Assurance Level conclusions for electromagnetic compatibility.
e. Use of particular risk in determining the environmental threats assessments may also be considered.
f. Include ground path determinations within the assessment sheets particularly on the schematics. (Electrical ground paths were not found in any of the literature searches as a deliverable for the design program.)

More details associated with bond path elements and bond techniques were also updated in the methodology chapter of the thesis where the original assessment sheets were proposed. The general layout of the final proposed methodology and the initially proposed methodology were also affected by the case studies exercise with regard to electrical bond path descriptions. A return loop was added to the methodology to address data that may be available from the aircraft designs that are already in service. This information can further refine the outputs from the methodology if included in the assessment sheet for comparison to the newly proposed designs.

As literature searches were conducted in the case studies on the design processes through investigations of test and certification documents, more detailed examination was conducted of an aircraft program development process. One key finding was the use of similarity in the development of certification proposals. This technique is often applied to minimize design costs and accelerate the development program. When design similarity is used to claim that a design certification is completed by reference to a previous aircraft development program, it was discovered that past design techniques may be repeated without any more detailed examination of the continued airworthiness performance; such as that which is proposed in this body of work. Early designs were not as cognizant of the importance of electrical bond paths to electrical and avionics systems because there were simply less of these types of systems. As a result more detail was added to the case studies regarding design processes. The case studies examined design stages more deeply than the original methodology section anticipated was necessary.

The methodology as exercised through the case studies highlighted the value and importance of an engineering design integrator. The methodology was revised to include a signature/approval process integrating different disciplines through assessment sheet approvals. Early development of the methodology had not identified this approval process as important to successful deployment of the methodology. Additional data and details sourced from several different disciplines raised awareness that the integration of design constraints is very important to successful design optimization. The case studies gathered data from initial certification documents which were singularly focused within the sourced discipline. During the preliminary design phase, an integration function is important to create and manage in order to assess each design from multiple discipline perspectives as the implementation is determined. After completion of the case studies, it was determined that not enough emphasis was put on this integration detail and revision to the methodology chapter was needed to include this finding. A process was included to pass design decisions back through a design revision studies which includes reviews from multiple design disciplines. The final methodology included in this thesis contains steps that were added to the initial prescribed design process to address the design review requirements. Completion of the case studies to demonstrate the new methodology, allowed for the design methodology to be improved. These improvements include more actively incorporating the engineers who are aware of design performance issues within the preliminary design phase.

Additionally, an update to the methodology was created to pass the design, test, and service details on to the MSG-3 analysis process for a required maintenance evaluation. This process will assess the design robustness against the deterioration of the electrical bond path effectiveness. If designs are found to be less than robust for long term in-service application, the MSG-3 process will define appropriate maintenance. It is important to note that the design revision study included in the methodology feeds into the design optimization process and not directly into the MSG-3 analysis process. This is an improvement to past practices where non-optimized designs were completed and sent to MSG-3 with subsequent maintenance declared necessary. The design revision studies within the methodology are intended to evaluate the impact of any installed application to the long term performance established by the design goals and could potentially avoid maintenance if the design is revised. The design issues that may be identified at that point are worked within the design process and not provided prematurely to the maintenance determination process.

The methodology was proven to work when applied to an aircraft development program. The case studies provided improvements and understanding of the methodology.

6.2 Challenges to the Arguments

On a new airplane development program, one must appreciate the importance of decision making with regard to electrical bond paths. Often, electrical bond paths are determined by individuals responsible for a singular piece of equipment. This methodology challenges the present systematic design process for lightning protection electrical bonds. In future aircraft development programs, the importance of deploying such a methodology as proposed by this work only increases as the aircraft of the future become less metallic and equipment more highly integrated.

The aircraft examined in these case studies do not contain highly integrated systems. For highly integrated aircraft, the importance of designing the continued airworthiness into the lightning protection expands to include many more systems that may share electrical bond paths. The analysis sheets are designed to address this more highly integrated design and assist with the cross-organizational support that is necessary to succeed at designing highly integrated systems

6.2.1 How can this Methodology Success be Proven?

The success of the methodology is proven by considering the outcomes. When real design data was applied to the methodology, improvements to the design process and specific installations were identified. The case studies applied actual "real world" design data for assessment. Results of the review identified potential improved design solutions for some components such as system connectors and lightning strike metallic strips mounted to non-metallic surfaces.

Bond paths do not maintain the same resistance over the life of the aircraft. Testing has proven that application of salt spray does degrade electrical bonds that are not appropriately designed to defend against the resulting deterioration. Bond paths for electrical installations were described in detail. During a lightning strike event, lightning current travels along the structure of the aircraft. Wire installations will also carry current to the attached equipment. It was determined in the case studies that wire installations rely on bracket attachments to structure, equipment attachment to aircraft structure, installed shield wires to carry the additional current during the lightning strike event within the wire looms, and bonding jumpers that may attach between the brackets and structure or the equipment and structure. For each of these electrical interfaces, a specific impedance is required as part of the design to ensure that voltages generated by the lightning current are kept to acceptable levels. For an aircraft development program, the expected "standoff" voltage that any control equipment would experience at the junction from outside the equipment to the internal equipment control electronics is established by the design team.

Working with this requirement, designers for aircraft equipment establish appropriate electrical bonding schemes to ensure that the required voltages are within the specified levels. These designed impedances are measured at the time of aircraft production to ensure that they are within acceptable parameters determined by the design evaluation. The impedance however, will increase over time as the electrical bonds deteriorate. It is these deteriorated electrical bonds that require more attention at the time that the design is developed. Unfortunately, electrical bond degradation curves do not exist to assist in these design decisions. The relationship of corrosion that causes electrical bond degradation to the impedance of the electrical bond is difficult to produce. This is an area that may be explored to enhance the application of the methodology. Experts in the lightning protection discipline maintain that the prediction of the deterioration of an electrical bond is not possible since the exposures to the elements that cause the deterioration are variable. In design of aircraft structure, degradation such as fatigue and corrosion are modeled to assist in the design development process. In the case of aircraft structural design, measures are taken to address the real problem of corrosion and fatigue. A similar measure must be taken for lightning protection by first identifying the real problem as attempted in this thesis and then creating techniques and tools to address lightning protection continued airworthiness. The methodology proposes a way to address electrical bond deterioration through use of test information but may be served by further investigation into electrical bond degradation modeling.

6.2.2 How Important is Data Gathering to the Success of the Methodology?

Data gathering is critical successful application of the methodology. The case studies proved that data gathering is critical to the success of the methodology. Though the methodology was exercised by several case studies using an already designed aircraft, the availability of design data was challenging. To some degree, the exercise could be improved by proactive incorporation of the methodology into a design program so that decisions can be made before the design is settled. The data gathered in the case studies also proves that past decisions can be evaluated for effectiveness on new aircraft designs. It is a matter of intent and desire to create a better performing design that will drive the interest in use of this methodology. One advantage however in performing the case studies on an aircraft that is already designed in a retrospect is the identification of the documents that will be affected for a new aircraft design. Understanding what certification documents will provide with regard to the design details, was achieved through the case studies exercise.

Integration

Some of the required data details for the assessment sheets are contained deep within the drawings on several sheets and do not converge in a single location. The case studies demonstrated the importance of integration within the design and also the importance of a data delivery system that supports the operation of the methodology. The assessment sheets assisted the effort of integrating information and design details but cannot be the only factor that drives the need for the data. A proposal comes from these case studies that suggest a design document should be created that collects the relevant to electrical bond path data which describes the designed path and its components in detail.

Equipment Criticality Associated with Data Gathering

The concept of equipment criticality was explored in the case studies in greater depth once the data was gathered. The difference between the criticality as determined by the FAR 25.1309 safety analysis and the safety determinations through the Design Assurance Level process associated with AC20-136 process were clarified. Findings were provided that demonstrated how a system considered non-critical by the safety analysis performed under guidance from FAR 25.1309 could be elevated to a hazardous or catastrophic level failure when evaluated by the lightning in-direct effects process in AC20-136. This observation emphasized the need for understanding the electromagnetic perspective for lightning protection safety determination and also highlights that direct application of the systems safety analysis results may produce an incorrect classification of lightning protection components. This incorrect determination of the lightning protection significance could drive incorrect protection applications. Data gathered in the case studies resulted in additional attention to these criticality determinations. The application of new or significantly modified systems as categories used during certification was also explained along with its potential impact to the proposed methodology.

Gathering Test Data

Test data from qualification tests were utilized in this methodology. Service experience with the bonding methods and component designs were also leveraged to produce the desired outcome of improve designs. Findings associated with connectors that perform poorly in service over some period of time were interjected into the methodology at the appropriate point in the assessment sheet. These findings need to be corroborated with test data and design determination processes to ensure that the best performing designs can be deployed in the appropriate locations. For application of these and other potentially unknown inputs, the analysis work sheets need to remain flexible to account for potential expansion of the analysis process.

Electrical Bonding Data

Further development of the case studies through data gathering investigated the importance of electrical bonding on aircraft. Literature searches resulted in discovery of an electrical bonding design guide developed by the OEM that was in need of update to bring the bonding practices developed for the new aircraft design processes into the forefront. In a real development scenario, the methodology may rely more heavily on such a design guide to perform in-the-moment design decisions regarding the electrical bonds. Reference to this design guide was included in the case studies. The importance of an electrical earthing design guide was highlighted and inclusion of the design guide into applications of the methodology resulted. For early aircraft designs, it was thought that sealant may not be necessary, especially in applications where a bond jumper or earthing wire was attached to a piece of equipment that may require removal for maintenance or overhaul.

Use of Sealants for Installation of Electrical Bonds

Through research of the data gathered in the case studies, it was discovered that sealant applications are an important part of lightning protection continued airworthiness. Sealants may be applied after the terminal joint is assembled. In the industry, this is referred to as a fillet seal. Fillet seals have been identified in service to increase the possibility of trapping moisture when used in sealing applications outside the pressure vessel. The phenomenon is brought on by an imperfect fillet seal application that may include a small unseen void in the sealant. In this case, the void would act like a siphon when the aircraft is cycled from standard ground atmosphere to a much greater altitude pressure. Data gathered for the case studies uncovered this issue. Understanding appropriate applications of sealants, appropriate types of sealants, and the relationship to the continued airworthiness of the installation was achieved through the case studies information surrounding this topic. As a result of this learning, the analysis sheets that drive the assessments for continued airworthiness were revised to include the sealant application and type. In a similar manner, cleaning methods associated with preparation of electrical bonding installations were explored and included within the analysis. Specific electrical bonding information regarding the aircraft in the case studies was acquired through literature search and is included within the case studies.

Data gathering that was accomplished during the case study exercises enhanced the methodology and enhanced the understanding of its application on an aircraft development program.

6.2.3 Does the Validation Substantiate the Case Studies Findings?

The validation was accomplished on a simple lightning protection design for nose cone lightning diverters. As part of the case studies, the nose cone lightning protection on the aircraft under study was also evaluated. This evaluation was more detailed than the validation exercise. Some additional details gathered for the case studies resulted in a better understanding of the methodology such as the information gathered on the certification of the nose cone. In investigating the nose cone certification, the topic of component criticality was raised and researched. Lightning protection is categorized by different certification processes resulting in a need for corroboration of the certification basis for lightning protection components.

Determining the Significance of Criticality

The classification of the lightning protection as “critical” was not mentioned in the validation. The inclusion of design goals stresses that every protection device or design must be determined to be critical or not critical in order to properly assess the design. Debates can take place on aircraft development programs regarding this criticality determination, however, the final declaration of criticality in the certification documentation must be included in the methodology assessment sheets. At a later point in the development of the case studies this criticality determination was included in the assessment sheet formally.

Indirect Lightning Effects

In the case of the lightning diverters evaluated in the validation, the protection was provided for the direct effects of lightning. This validation was not able to address whether the indirect effects of lightning could also be evaluated using the proposed methodology. The case studies section of the thesis addressed this issue by including several case studies of both direct and indirect effects lightning protection. Validation of the need for an integrated design organization was also not possible with the validation. This may be due to the limited scope of the validation. Integration of design solutions is a key to success. The near seamless ability to share data among aircraft designers was identified in the case studies. The development of how this new concept is integrated into a design group is a good candidate for the continued development of the methodology and future work.

Design Integration Function

As the methodology was repeatable across multiple lightning protection design components in the case studies, it became apparent that an integration function was necessary to be made part of the methodology. The importance of an integration function was not discovered in the validation. The validation was adequate to test the use of assessment sheets but did not provide the depth needed to understand the importance of design specifications, design manuals, and the innovative use of these design guides. Certification was also not discussed in the Validation of the methodology. Research of certification processes in the case studies uncovered certain issues such as similarity of components certified on previous aircraft certification programs. The use of "similarity" to past designs in the certification process will reduce the amount of engineering activity required to complete a design. This reduction may result in fewer design assessments as the assumption of similarity is that the fit form and function are unaffected when similarity is used as a way to certification. The case studies found that even for components that are similar to past designs; it would be highly valuable to establish the assessment sheets since certification status for components is not a guarantee of long term component performance.

Different Classes of Case Studies

Input from the Cranfield University supervisor (Professor Fielding) requested additional test cases. Comments regarding scope, number of test cases, and which cases were appropriate to fully exercise the methodology, led to specific choices made to include the most diverse set of case studies. In one case, the lightning protection components on both composite and metallic materials were chosen to demonstrate the differences and guide the case studies toward a more successful exercise. Additional comments were provided from the PhD supervisor regarding the improvement of an existing design vs. a new design. This led to a section in the Chapter 5 of this thesis that describes more thoroughly, how to deal with revolutionary designs. From these discussions, the investigation was expanded to describe the certification processes, especially the use of design similarity in reducing certification testing requirements. The case studies introduced the concept of revolutionary designs and further development of the meaning of design stages (Conceptual Stage, Preliminary Stage, and Detailed Stage). This investigation increased the amount of data included in the case studies generated by literature searches on the subject of design phases by researching further into the development process.

The case studies included more details of specific lightning protection designs on the aircraft and descriptions of the protection components than was possible with the validation. As such, the case studies expanded the validation to test the methodology even further. At this earlier stage in the development of the case studies details regarding the aircraft environment, aircraft environmental threat data, and associated details of the wire installations criteria regarding vibration, temperature, and moisture-prone areas were added to the case studies. The validation did not perform such a detailed assessment as it was determined to be very impractical with such insufficient data. Further development in the case studies that were not included in the validation was in the area of lightning impacts on aircraft systems. Explanation of a lightning threat, faradays law, and the discussion surrounding the effects of lightning on aircraft transport elements such as hydraulic tubes were incorporated into the case studies. More examples of the different paths through the design process was provided with detailed explanations regarding the varied sources of information on an aircraft development program that lead to lightning protection continued airworthiness and maintenance requirements.

Maintenance Requirements

In earlier versions of the case studies, and within the validation, the inclusion of maintenance requirements was not considered germane to the methodology. At later stages of the case studies development, the incorporation of maintenance as an alternative to the redesign of a lightning protection component was included as part of the methodology and was also included in a revision to the design assessment sheets. In this stage of the case studies work it was also determined that instructions for lightning protection inspections performed on the aircraft after a lightning strike attachment would provide a good understanding of the things within the design that most aircraft manufacturers consider important. These things were listed in the unscheduled lightning strike inspection and were included in the thesis. Research into the aircraft maintenance manual and across several different aircraft support manuals provided information that was included in the case studies defining the general principles associated with aircraft lightning protection inspections. For lightning protection designers, this knowledge is a great enhancement to understanding continued airworthiness issues associated with the potential damage to the aircraft after a lightning strike.

Incident and Accident Reports Impact Instructions for Continued Airworthiness

Also within development of the case studies, a few aircraft incident reports were included to form legitimacy to the potential outcome of poorly designed or poorly maintained lightning protection designs. This data is sourced from legitimate regulatory investigations. These investigations lead the reader to understand not only how lightning can affect the continued safe flight and landing of an aircraft, but also provide information on the importance of maintaining lightning protection. In one case the evidence of missing or improperly installed bond jumpers (earthing wires) was found to be very important information for understanding the significance of continued airworthiness. The design failure in this particular incident highlighted a key design specialty to assess continued airworthiness as postulated and if done properly; can have positive effects on the aircraft operation and impact the safety of passengers and flight crews. In the same case, both passengers and flight crew were harmed by a hard landing due to the reduced controllability of the aircraft after the lightning strike and subsequent collapse of the landing gear. In another case, lightning was suspected to have caused a complete electrical failure which resulted in the loss of all the lives of those on board the flight. Revision to the aircraft flight manual has been recommended requiring inspection of the aircraft after lightning strike where loss of electrical power results from the strike among other specific recommendations such as specific positioning of the cockpit torch.

Component Similarity Strengths and Weaknesses

Another lesson from the case studies work is that further investigation of component similarity as a way to define acceptable design is needed. In an aircraft development program, similarity can be useful to reduce development costs; however it was determined during the development of the case studies that some of the assumptions regarding the lightning protection performance were based on aircraft designs that were developed over forty years ago. This confirmed the idea that the methodology can examine assumptions without the requirement to actually design and test new alternatives that would replace the designs if using similarity as an argument for acceptable certification was not an option. In one way of describing the advantage of this methodology, the use of the assessment sheets and the methodology can offer a simulation of the outcome without committing precious certification funds to determine the new design viability. Because of this issue raised by the research associated with the case studies work which was not evident in the validation, more research in aircraft design handbooks was conducted and also included in the Chapter 5 of the thesis.

6.2.4 Are there any Industry Opinions on the Theory?

Research conducted during development of the case studies identified a study by the National Institute of Aviation Research (NIAR) which determined that aircraft that are fully protected from lightning adverse effects had a significantly lower percentage of electrical failures. This discovery leads to the conclusion that the methodology demonstrated in these case studies would bring a significant value to the aircraft design process and reduce maintenance costs. Examination for continued airworthiness of lightning protection is critical since lightning protection is not an active system that is able to provide indication of protection degradation. Some more advanced systems installed on aircraft are incorporating a messaging system that would indicate a lightning strike has occurred on certain structural components. This is accomplished through application of a “smart” layer of material on the outer exterior of a particular piece of structure. When lightning strikes, the layer is damaged and small circuits within the layer send a signal to the aircraft avionics system that a strike has occurred. These type of systems may be incorporated more extensively in future designs as the value of the indications are analyzed and understood. Similar exploration is taking place with the advent of

Integrated Vehicle Health Management (IVHM) systems and devices. Inclusion of active lightning protection device systems may be a future IVHM development.

In a paper presented to the Society of Automotive Engineers (SAE) [6.1], Jean-Patrick Moreau from Dassault Aviation states that the intent of the L/HIRF protection maintenance tasks is to reduce the possibility that a single failure cause (such as a lightning strike), and the occurrence of a common failure cause (such as ED or AD) across redundant channels of L/HIRF protection, could impact aircraft airworthiness. In order to determine appropriate maintenance, Moreau suggests that a system be developed to grade aircraft characteristics such as:

- Inspectability of protection
- Susceptibility to accidental damage
- Environmental assessment
- Criticality of the lightning protection

This validates that in order to assure continued airworthiness, an evaluation similar to that defined by Moreau is required. The main departure in the hypothesis within this thesis is that this type of evaluation can be performed as part of the design development to leverage even greater benefit to the design before the design is fixed and unable to change without great impact to the development program.

In a paper written by C.C. Goodloe at the Marshal Space Flight Center in Alabama USA, guidelines for protecting aerospace vehicles from lightning strike related incidents were considered [6.2]. In this paper Goodloe describes the basic steps in designing to withstand lightning as:

- Determine lightning critical Systems
- Determine lightning strike zones
- Define the direct effects protection
- Define the Indirect effects protection
- Lightning protection measures
- Successful lightning protection design and certification
- Electromagnetic effects control plan
- Pass-fail Criterion

Goodloe contends that these steps provide a methodology that is proven to work on prior aerospace vehicle projects. The method is valuable for design engineers to follow but omits the additional step to ensure that the designs chosen are able to withstand the installation threats that lead to protection degradation. Goodloe recognizes that early participation in the design process is relevant, similar to the conclusions of the methodology in this body of work. Goodloe however, declares that following the methodology he has outlined in this technical paper for the US National Aeronautics and Space Administration (NASA) will produce an adequate lightning protection design. This may be true in a limited sense in that it may produce an adequate design at the beginning of the aircraft life, but he does not address the continued airworthiness of the lightning protection designs.

Keith Armstrong from Annex A Aerospace has developed a methodology for electromagnetic hazard protection design and clearance [6.3]. The framework described in this Annex paper to the IEE organization electromagnetic compatibility guidance document describes modeling of the lightning threat, reference to design guides for installation performance in electromagnetic environment, development of the equipment, qualification testing and finally on to clearance. Though this model has some resemblance to the methodology presented in this work, Armstrong does not address the continued airworthiness of lightning protection designs. This demonstrates that the subject of continued airworthiness included as a design criteria for creation of a robust aircraft vehicle design, is overlooked by most experts in the field of electromagnetic aircraft protection design.

In summary, challenges to the arguments presented in the thesis and evidence that the methodology addressed the challenges are as follows:

- The methodology success was proven by positive design revision outcomes provided by the assessment sheets and validated by aircraft service data
- Data gathering, integration, and corroboration including test data and certification criticality data is key to the success of the methodology
- Establishment of lightning protection criticality is necessary and may require determinations that cut across present aircraft systems safety assessment processes requiring integration of the protection assurance way forward
- The validation provided an indication that the methodology was reasonable while the case studies further developed the methodology and realized benefit to the designs
- Industry opinions on the theory do not consider the continued airworthiness as part of an integrated design process demonstrating a need for the proposed methodology

6.2.5 Why Haven't Aerospace Manufacturers Done This Already?

Cost to recertify already certified systems and legacy certification practices are two reasons why this methodology has not been implemented to any great degree by manufacturers. It was discovered only recently with the emergence of highly integrated and electrically driven aircraft systems that the lightning certification process has a large impact on the lightning protection design development. Further research about the certification process and its impact on the methodology was included in Chapter 5. In cases where components were certified on past designs and previous aircraft development programs, additional design assessment may not be deemed necessary by the engineering leaders. Since no further evaluation is conducted on these previously certified designs, this could lead to sub-optimal designs and the perpetuation of design features that could be improved for continued airworthiness if the methodology proposed with these case studies is used. The case studies work also led to understanding that the methodology could be used for both new and reconfigured or derivative aircraft. Designs that are adopted from past certification programs may be acceptable for certification i.e. low risk, but may not be examined for potential optimization unless a technique is used leveraging the advantages of the methodology proposed in this research.

From the case studies development, it was concluded through review of all the certification and design documents that maintenance is not the focus of lightning protection development. In fact, research of the design documentation showed that maintenance is simply a secondary process that is performed after the design is complete. After conducting the case studies on several lightning protection designs it was determined that both the design and maintenance can be optimized with the use of the design assessment methodology. Changes to designs may be recommended and subsequently evaluated for practicality by use of a feedback methodology added to the early version of the methodology.

Another reason that manufacturers have not included this approach in their design processes is simply because they did not think of it! This methodology is truly an innovation brought to the aircraft design process and is Patent Pending with the US Patent Office.

This type of collaboration between maintenance and design disciplines has not been previously part of design decision making such as proposed by this methodology. Later in the development of the case studies the concept of maintenance program development was introduced as part of the design development. This is not a normal industry standard approach as the maintenance program is generally determined after the designs have been completed. This early incorporation of the maintenance program requirements incorporates more advantage to the design methodology as it can further optimize the design not just for the continued airworthiness but also for the mitigation of maintenance costs later in the life of the aircraft.

The important points made in these lessons from the case studies are as follows:

- The methodology evolved in a favorable way during the 5 year study to include feedback loops from engineering departments and outside data sources such as test data from airlines, qualification testing or developmental testing
- Literature searches contributed to the revision of the methodology and identification of advantages the methodology can bring towards advancing regulations from initial article to end of life performance.
- Engineering design integration teams were identified as essential to enable the methodology potential and maximize its effectiveness
- The MSG-3 analysis process will benefit in reducing maintenance from the receipt of more mature long-term design solutions due to this methodology
- With application of actual design data as provided in this body of work, design improvements were identified that were not included in the original design drawing the conclusion from real data that the methodology can work if applied to an actual aircraft development program
- The application using multiple case studies for direct and indirect lightning protection, proved that effective data gathering is essential to the success of the methodology
- The validation of the methodology provided an early indication that the methodology had potential value
- Component similarity to past certification programs may not investigate continued airworthiness to the degree proposed by this methodology

- Legacy certification practices do not include a methodology such as the one proposed by this body of work
- Industry opinion as drawn from literature searches does not place emphasis on continued airworthiness within the lightning protection design process suggesting that this proposed methodology is innovative
- Highly integrated aircraft systems need more sophisticated means to address lightning protection continued airworthiness such as that proposed by the methodology
- Maintenance is not the focus of lightning protection design nor has collaboration between maintenance engineers and lightning protection design engineers been identified in the literature searches as a standard design approach

Chapter 7 Discussions

7.1 Introduction

The focus of this research was in the development of a design methodology for aircraft lightning protection continued airworthiness. The methodology provided a solution to a need in the aircraft design process for incorporation of a continued airworthiness constraint. The objective of this work was to solve the design problem to ensure continued airworthiness of lightning components after design and aircraft type certification is complete and the aircraft is put into service. All objectives defined in the thesis objectives were met. In the early efforts to conduct the case studies, the objective to use data from several OEMs was not met due to complications with the proprietary nature of the information and the resources needed by the OEM. In the most current approach, the author sought out OEM data from one manufacturer and created a contract to successfully conduct the analysis. Providing for the continued airworthiness of lightning components is particularly important since most of these components operate passively and fail in a latent manner. Evidence that lightning protection components can fail fairly soon after the certification of a new aircraft type have been identified in this research.

Different areas of investigation were conducted. Case studies were performed to investigate the potential application of the methodology in the following areas:

1. Design methodology for continued airworthiness of lightning protection components
2. Direct effects structural lightning protection
    a. Nose Radome Diverter
    b. Antenna Cap Diverter
    c. Rudder Tip Diverter
3. Indirect effects lightning protection
    a. Auxiliary Power Unit control equipment, wiring and connectors

This chapter discusses the objectives of the research and methodology, how they were met, what gaps in current design methodology are filled with this proposal and how the methodology is deployed within an aircraft design theater. Details on how this research advances the design of an aircraft will be collected in this chapter. Reflection on advances in aircraft design methods will be provided in light of this work as well as potential limitations and advantages given application of the methodology within an aircraft design program.

7.2 The Design Methodology Application and Limitation

The design methodology developed in these studies center on the concept of utilizing known elements of lightning protection component performance in the development of new designs. This fundamental thought is simple in principle, but also has been found through research contained in this body of work may not to be practiced in fact. From the research, the practices identified for development of lightning protection components rely heavily on the use of past practices and previously certified designs. The reason that this current practice has been found to be sub-optimal is that the continued airworthiness of past designs is not considered a design constraint in the initial design of a lightning protection component. Rather, current practices consider lightning protection components to be either adequate for the life of the aircraft or adequate until failure requires a repair or replacement of the component. The principle that a lightning protection component can fail in-service and will subsequently be repaired or replaced thus reinstalling the previous certified level of availability is acceptable if one can rely on the component failure to be evident to the operating crew. Since most lightning protection components are passive, this design principle needs further development such as that presented in these studies. This body of work challenges the practice of developing lightning protection designs without continued airworthiness in mind by using an example of a previously certified aircraft.

The methodology proposed in this thesis can be adapted in other design disciplines as well, though that possibility has not been part of this investigation.

The results of several of the case studies in this thesis lead to improvements in the resultant designs which demonstrate the value that is gained through the implementation of this methodology.

Finally, a comment on the implementation of the methodology is necessary. The methodology uses an interactive and iterative technique where several disciplines within a design community interface in a way that is not currently required. For instance, test engineers would normally test a component, revise inputs to the test and provide the design community a set of data (results) that can be used to prove that the component can be successfully deployed into the aircraft design. This data is sometimes used to qualify a component or in other cases may be used to perfect a design. The test report is referenced in a certification plan as a way to prove the design is worthy of the required duty. Once the certification plan is accepted, the aircraft design can be fixed and an aircraft can be built using this design, which then meets the intent of the design objectives and regulations listed in the certification plan. The uniqueness of this methodology is the inclusion of continued airworthiness design criteria equally with other design criteria early in the design development. The alternative to this methodology deployed in most aircraft designs today is the development of instructions for continued airworthiness after that aircraft designs are finalized.

The objective of the research to find a way to improve lightning protection design practices leading to better continued airworthiness performance was reached through the development of a new design methodology. Engineers that use this methodology will learn through implementation of the methodology that past practices are not necessarily the primary tool for selecting design solutions. Additionally, the engineers will learn that continued airworthiness is a design constraint that should be integrated into the front end of the design process rather than being left to chance after the aircraft receives type certification. This was learned after completion of the case studies where new and better long-term performing alternatives were determined to be applicable, through the completion of the design assessments.

Though this design methodology has not been applied in practice, similar analyses have taken place within the maintenance program development MSG-3 analysis. The problem with relying on MSG-3 analysis to assess the design continued airworthiness is the late point in which MSG-3 analysis is conducted in an aircraft development program and lack of integration of MSG-3 analysis with the design methodology. Since MSG-3 analysis is performed on completed designs, issues that may be identified by MSG-3 analysis are difficulty to resolve at this late point in the program. In this case, either scheduled maintenance is recommended or costly design changes are recommended that could impact the certification plan. It is recommended that this methodology be applied on aircraft design programs in order to avoid the identification of design issues after the design program is completed and submitted for certification.

In order to make the methodology operate effectively in practice, the research determined that design engineers should consider the importance of a robust data gathering method. This methodology relies on test data, performance data, and experience with certain lightning protection component design implementations, as well as familiarity with the operating environments. To create the most effective design practices within the aircraft design community, performance data must be shared, discussed, evaluated and final design dispositions created.

The limitation in the thesis was the use of design data from an aircraft design program that had concluded over ten years ago. The way this limitation was addressed was by research into the certification documents used at the time of the original design completions. Since the original certification documents could be accessed, the decisions and reasoning for certain design implementations could be included in the methodology. This approach simulated a new aircraft development program, looking at past design decisions and evaluating the potential recommended options going forward even in spite of the final design implemented at the time. These alternatives were developed by use of a Lightning Protection Design Assessment Sheet developed by the author to simulate a design community activity necessary to demonstrate potential outcomes of the case studies. As anticipated, some of the case studies recommended different design solutions than what was selected at the time of the original design development. This idea to use cross-discipline assessments will require process changes for data collection, distribution, and application.

Another limitation is in how one would deal with the use of "hind-sight" as a way to prove that a better solution could be obtained using this methodology if the methodology were deployed at the time of the aircraft development. One argument to this limitation, may be that translational thinking is the real genius in the methodology. Using what is known about certain design performance such as how a particular material conductivity degrades given certain environmental operational threats, is one way to overcome unknown performance details of a particular lightning protection component. In this case, measurements could be gathered from mechanical systems that do not require continued electrical conductivity in the makeup of the installation and applied to the lightning protection component designs as a way to assess the continued airworthiness without having specific data for that particular component in hand. If this approach is used, the question about whether the case studies provided the required test of the methodology can be answered positively.

7.3 Discussion on Methodology Process, Utilization, Implementation and Validity

The case studies identified the association of electrical bonding and grounding (earthing) knowledge to the lightning protection continued airworthiness. The validation exercise gave an indication that further development of the thesis had the potential for discovery. Electrical bonds that are important to securing proper lightning protection were examined. This examination was accomplished by application of the methodology to direct lightning protection components and indirect lightning protection components. This was done to test the adaptability of the methodology. In evaluation of the results, the methodology is very adaptable to both direct and indirect lightning protection. This is proven in the case studies be definition of the component characteristics to express the different component features that may be relevant to continued airworthiness. In many cases the characteristics under review were the physical elements of the protection component that allow for safe passage of the lightning current. These characteristics became the focus of the methodology more than the actual protection components themselves. Remember that all the protection components in these studies were passive protection devices that do not make failure of the lightning protection evident. Further work can be done, and should be done, in the area of developing active lightning protection systems. This may affect the work in this thesis but will in all likelihood not affect it negatively; rather this kind of exploration is highly likely to compliment this work and lead to additional new knowledge. In the different case studies it was determined that protection of the lightning protection characteristics is most important that the protection of the lightning protection components themselves. Since it is the characteristic of transferring electrical energy that is most important, then it followed that the evaluation within this methodology should be directed at those environmental conditions that effect on the characteristics long term robustness and availability.

7.3.1Data Distribution and Assessment Sheets

After the assessment sheets were developed, they were tested by the validation exercise. The validation exercise was not able to test the need for robust controls over the distribution and utilization of the assessment sheets due to its simple singular nature. Information gathering needed for development the case studies were tedious and demonstrated that an integrated process for including the lightning protection design continued airworthiness requirements would be recommended. Use of these integrated assessment sheets would be appropriate during the development phase of an aircraft design program. Also, it was noted that implementing the methodology in real time as an aircraft is designed would remove some of the tedious "discovery" of data since the design team would arrange for the transfer of the required information; more directly that the anthropological exercise used in the test cases. Use of assessment sheets was appropriate to demonstrate the methodology within the case studies; however, a database would be much more useful and effective in dealing with large amounts of data distributed over many specialist engineering groups and suppliers. The association of the design threats contained in the case studies and specific lightning protection components information regarding the installation techniques, yielded conclusions within the assessment sheets that provide further design engineering guidance. Combining this assessment with service experience can be even more impactful to improving the design. This result taken from the outcome of the design assessment sheets evaluations was evidence of the value of the methodology.

Implementation of this methodology can be accomplished by use of the assessment sheets design to implement this methodology and an integrated design team. Challenges to the implementation may exist in the engineering team organization and the existence of departmentalized skill sets. Since the electromagnetic design and electrical bonding and grounding skills are departmentalized, the assessment sheets provided evidence that cross examination between these two skill sets would benefit the final design outcome. The aircraft design process is iterative in nature. The use of the assessment sheets in the case studies definitively demonstrated that feedback from design assessments is a superior approach especially when a lightning protection component is found to be inadequate for the life of the aircraft. An example of this was included in the case where a connector design was found to be inadequate for the application outside the pressure vessel and a change was recommended to the connector type to be selected for this design application.

7.3.2 Detailed Discoveries

The case study exercises provided a few discoveries that should be considered valuable if the methodology were adopted on a new aircraft development program.

1. **Continued airworthiness after the design is fixed***.* The first discovery was that the attempt to drive continued airworthiness requirements backwards into the original design of the aircraft components through the maintenance development process is not effective. Use of the methodology would drive out less maintenance through optimization of the designs to consider continued airworthiness at the beginning of the protection component design process. In fact, the maintenance program development program cannot synchronize

effectively with the design development phases since adequate design details are not available early in the program; nor is the MSG-3 process equipped to evaluate and drive 'backwards' requirements for design revisions as is proposed in this design methodology. Maintenance program development using the MSG-3 methodology occurs after the designs are fixed which is too late in the aircraft development program to manage effective implementation of continued airworthiness requirements. MSG-3 is not an appropriate tool to determine optimized designs.

2. **Early adoption of long term solutions is required***.* The second significant discovery was that lightning protection characteristics need to be determined early in the design phase and need to be considered for long term viability given a defined installed environment. Thus, given the application of this proposed design methodology, lightning protection component critical characteristics can be determined earlier in the design process. From observations in the data collected for the case studies, there does not seem to be enough attention given to the determination of materials and finishes for long term electrical conduction early in the development processes. As an example, the proposed methodology has the establishment of critical characteristics for each component at the beginning of the detailed design stage. Step three within the methodology is where the critical characteristics such as the lightning shield material and finish are determined. This is proposed in the thesis to be the same as it is today, however further consideration should be provided to the possibility that the critical characteristics in step three be moved to step two at the preliminary design stage where identification of critical and essential lightning protection components in the installed environments are provided by the design team. This may provide benefit to the methodology further by providing visibility of the importance of the materials and finishes conductive property robustness earlier in the program. An example of this may be use of a tin plated copper shield on a wire loom outside the pressure vessel. The resistance of the indirect protection provided by tin plated shields is well established in the industry; however, there have been findings of degraded tin shields outside the pressure vessel due to the inability of these shields to resist corrosion. If a tin plated copper shield is chosen at the beginning of detailed design as proposed in the new methodology, it may be too late to revise the shield without major impact to the connector back shell in which the shield interfaces to provide protection to the loom. Changes in wiring designs at the detailed design phase of a program can have negative impacts on the suppliers and component manufactures. A significant finding of the case studies is that certification and past design development practices do not support an outcome of optimized lightning protection designs.
3. **Using similarity to past designs as a certification strategy forgoes opportunities to improve continued airworthiness designs.** The next discovery was the application of certification practices that are currently in place leads to the adoption of past designs without necessarily evaluating the designs against in-service performance data or even against potentially new testing techniques and standards.
4. **Current test practices do not consider detailed continued airworthiness design criteria.** After review of the EMC test reports generated at the time of the

aircraft design program, it was noted that the continued airworthiness of the EMC protection under test was not included as a category within the report. Avoiding testing parts or components that are already installed on other certified aircraft may be done to avoid new testing costs. The lightning protection certification strategy impacts how a component is assessed for use on new aircraft applications. The use of 'similarity' to past designs may be a cost saving proposal but will not require any additional testing that may have a great impact on the understanding of the component continued airworthiness capabilities.

5. **The methodology is flexible and can apply to new designs or already completed designs.** The methodology proposed in this thesis can be adopted whether new certification procedures are used or even if the components are certified by similarity to past applications. Past processes evaluated lightning threats in aircraft lightning zones and determined the appropriate designs that will protect the aircraft.
6. **Through case studies it was determined that design changes can be made to improve the design using this methodology.** After performing the case studies, it was discovered that the selection of lightning protection schemes may be altered if consideration for FAA FAR 25.1529 (Instructions for Continued Airworthiness) is included in the protection design selection criteria. Consideration of this regulatory requirement leveraged by the methodology developed within this body of work will impact lightning protection designs in a way that was not performed on past aircraft design programs. Requirements for sealants, composite structure assembly, electrically conductive bond paths, and the protection of these components has been proven by these case studies to generate differences in the design outcome than those produced using past methodologies.

7.3.3 Inadequacy of Failure Hazard Assessments

During the case studies exercise, the relevance of the failure assessment process became of interest since lightning protection failure can affect aircraft safety levels. Investigation into the lightning protection component relationship to the failure modes and effects analysis revealed that the lightning event may be used as a top level event however, lightning protection component failures are not included in that analysis. This resulted in further research into the techniques used to assess lightning protection component safety and a large amount of material was gathered in the case studies from the findings. The case studies demonstrated that the use of a failure hazard assessment is not enough to address the lightning protection design robustness over the life of the aircraft. The concept of design assurance levels was introduced within the case studies that assisted with the necessary categorizing of lightning protection systems. However lightning protection components seem to be in the shadows of other higher order systems analysis and not a focus for the aircraft level safety analysis. An entire section of the case studies was dedicated to the concept of safety and the different processes associate with design assurance for lightning protection. The use of this methodology brings focus to the lightning protection component certification resulting in further evolution of the certification process for lightning protection components. This may be an area of future work.

7.4 Way Forward and Future Work Required

The future work that is most relevant to contributing to this body of work is advancing the understanding of electrical bonding capabilities at the end of life of an installation on an aircraft. This modeling has not been made available to the industry. There are certainly issues with such modeling as the effects of aging on lightning protection components may not be linear nor may not be simple. Electrical bond degradation modeling is an area of study that would propel the acquisition of knowledge in this area of aircraft design to new levels. In addition to gaining understanding of this aging effect, further work can be done to incorporate the known SAE design criteria directly into the assessment sheets by reference. This area of development raises another area of development to include requirements for continued airworthiness into the SAE Aerospace Recommended Practices (ARP). Since SAE ARP guidelines are used for component and aircraft lightning protection design, it is prudent to work towards updates on these ARP documents to include more guidance for continued airworthiness. With the advances of aircraft systems architectures, another are to include in future work is the protection of components from EMC and EMI especially with regard to wireless control of aircraft systems. Although there are quite extensive design requirements for addressing negative effects of EMC and EMI, there is little to no work being done on the continued airworthiness of EMI and EMC protection.

Further development of the assessment method can also be an area for future work.

1. One improvement to the assessment process may be incorporation of a materials chart in the assessment sheets. This will bring attention to the significance of material compatibility to the designers supplying the data.
2. Another future work idea is creation of a risk index to ensure that certain lightning protection designs get the proper attention for continued airworthiness. With the large integration of systems on future high-technology aircraft, the sheer amount of systems data may make this methodology difficult to move quickly. A risk index may be a good solution to ensuring that the most important lightning protection schemes are evaluated with the right priority.
3. Along these same lines, a concept for determining zonal safety and threats to safety may be pursued. The development of zonal safety analysis for systems in particular zones will help sharpen the analysis when certain zones that contain particular lightning protection are evaluated. Some zones may not have high system safety ratings since the failure or degradation of systems within that zone does not impact catastrophic safety events.
4. Another addition to the assessment is the evaluation of component location. If a component is determined to be low in robustness when installed within a specified environment, the methodology may be revised to include a component relocation proposal.
5. Included in this future development might be ratings for environmental threats. After evaluation of the process used to create the criticality matrix produced by the FAR 25.1309 (System safety assessment process) one may create a parallel method that can be used for the threats evaluation. In consideration for future work, the revision of the methodology to directly tie the environmental threats

design criteria and the approved parts list process into the methodology and assessment sheets requires serious consideration.

6. Similar to rating criticality of zones, another area for future development is potential consideration of the FMECA failure mode effects and criticality determinations to be directly integrated into the analysis sheets. Ranking in terms of more critical designs to less critical designs may provide efficient application of the methodology. Using a System Safety Assessment (SSA) output, a matrix of severity and probability (Catastrophic, Major, Minor FAR 25.1309) may also be incorporated into the assessment sheets. These design outputs will assist the lightning protection design engineers in applying appropriate focus to the tests required of lightning protection components and ensure that the more critical systems are prioritized within the methodology appropriately. Safety assessments can be conducted after 25.1309 failure hazard assessments are complete and then additional assessment from the Design Assurance Level (DAL) found in the EMC design process to identify the lightning protection component significance within the assessment.
7. Lightning zones may also be better integrated into this proposed design methodology. Lightning zones on the aircraft identify the severity of the current and probability of the strike to attach in that zone. The assessment model for lightning protection components may benefit from including of the zone in the assessment sheets. These sheets were revised during the case studies exercises to accommodate this feature but may need further development to combine lightning zone severity with environmental threat severity in order to derive a proper zone rating.
8. In general, further work on the format and content of the assessment sheets is needed. Included in this work should be consideration for a database to manage the assessments. As part of the assessment sheet enhancements, the requirement to test the component resistance at time of installation may be helpful to add to the assessment sheet. These bonds are important to be installed properly but current systematic approaches do not include the examination of the installation process or design to ensure continued airworthiness of the installation is maintained.

7.4.1 Methodology Improvements

As this methodology relies on data to make it work properly, there are many data-related improvements that can be developed in future work. Expansion of the Step 9 "Perform Design Revision Study" of the methodology in Figure 3-2 can make the revolutionary designs even more advanced before an aircraft design project begins. Figure 7.1 describes the inclusion of revolutionary designs within the methodology.

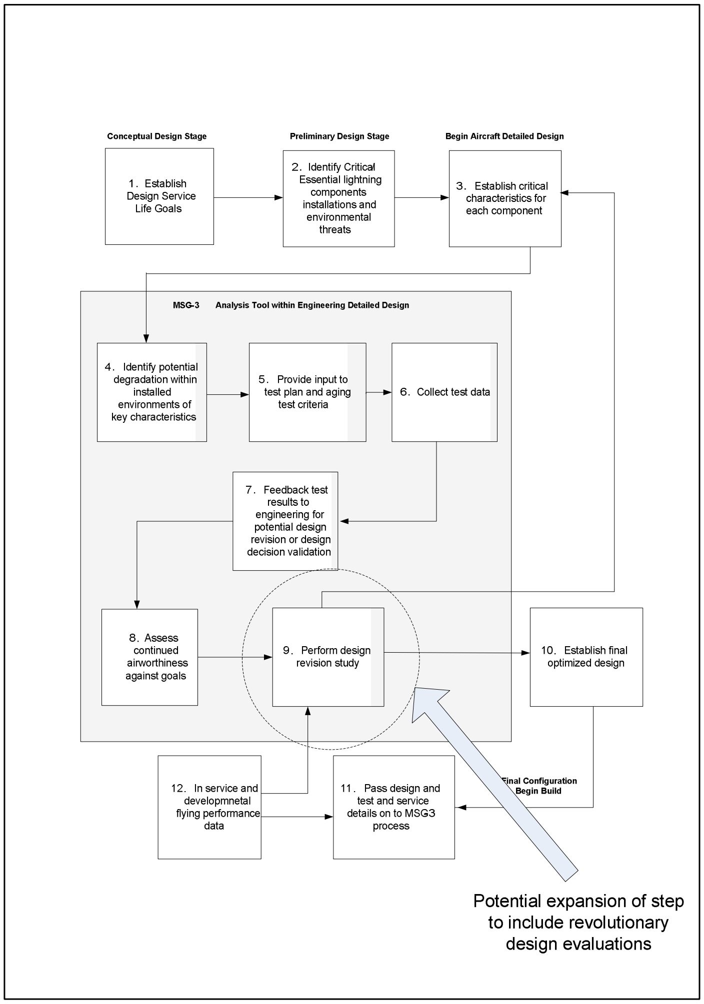


Figure 7-1 Revolutionary design evaluation modification to methodology

Certification tests are not generally performed to test which design will work or test alternatives for design implementations. This is simply too expensive. For Step 9 “Perform Design Revision Study” in the methodology, the chief engineer needs to consider an organizational structure that can utilize exploratory testing as a way to determine design solutions. Usually, this type of testing is called engineering tests or developmental testing and is not used as a qualification test. For these exploratory test scenarios, the organization may be required to assemble exploratory test “development” even before the preliminary design stage of the project. This kind of ingenuity integration is needed to avoid design delays, progress interruptions and retests for designs that were imagined but not produced. It is perhaps not a revolutionary idea and costs are usually the reason that many tests are not conducted, but with the advent of a test data repository and incorporation of the reusable data concept, better design data can be made available to many aircraft design programs. These data are simply under leveraged in the current format. Focus on the benefits of such a system is likely to produce a new plateau of knowledge from which further designs can leverage more advanced implementations.

7.4.2 Improvement in Methodology from Literature Search and Case Studies

Improvement of Step 8 “Assess Continued Airworthiness Against Goals”, in the methodology shown in Figure 7.2 could be provided by inputs from a continued airworthiness advisory board. Creation of a board would require further development as to the authority of the boards and charter.

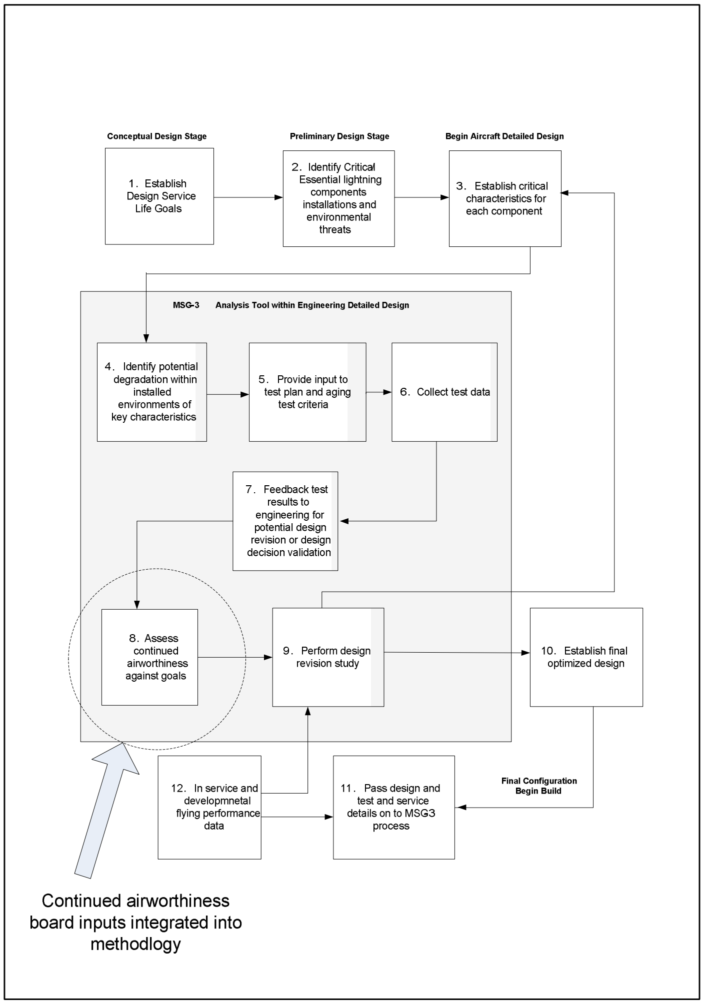


Figure 7-2 Inputs to methodology from Continued Airworthiness Advisory Board

On this board specific expertise should be represented such as:

- Maintenance engineering
- Reliability engineering
- Production test engineering
- Electromagnetic engineering
- Certification engineering
- Developmental test engineering
- Wire design engineering
- Electrical bonding and Grounding (Earthing) engineering
- Material processes and technology engineering

A description of the board responsibilities and functions of each board member mentioned in this list would also be required.

7.4.3 Corrosion Impacts to Continued Airworthiness

Corrosion was determined to be a significant factor in the continued airworthiness of many lightning protection components. A method for determining corrosion severity and the relationship between corrosion in a conductive joint and its relation to the conductivity is an area of required future work. For this, work is required to establish the most common materials in the conductive interface such as aluminum interfaced with titanium and then applying a controlled amount of salt spray to the joint while recording resistance of the joint as the corrosion increases. Tables can be generated with this information and a family of exposure levels can also be determined as a variable and recorded for each scenario. These tables should be tested with multiple test cases of the same material and moisture exposures to evaluate reproducibility of the results. Once tables of this nature are established, the information can be used in determining the expected outcome of certain electrically conductive interfaces within specific environments. These tables can also represent the impact to long term conductivity for different sealant methods and sealant types. With this additional development, it would be helpful to determine if patterns of degradation due to corrosion can be identified and a whether a predictive methodology can be developed for corrosion effects on electrical bonding characteristics.

Step 12 in the methodology “In service and developmental flying performance data” shown in Figure 7.3 calls for a report from the test engineer on the continued airworthiness expectations for the tested components. This is a very difficult task as test engineers may not be privy to the actual performance of similar parts already in service on other aircraft. A means for assessing the design is required in Step 10 “Establish Final Optimized Design”, also shown in Figure 7.3 of the proposed methodology. This is an area of future work required to ensure that appropriate balance is achieved in making the decisions regarding the significance of a particular test result. A gathering of data associated with continued airworthiness of lightning protection collaborated with the test engineer’s conclusions would be helpful in supporting this expansion. For many aircraft development programs reliability data is used to determine where certain systems should concentrate efforts for improvements. In the case of lightning protection, reliability data is most likely not collected through this reliability system. Since lightning protection is mostly passive, indications of lightning protection failures are difficult to isolate. Operational impacts to airlines related to lightning strikes that cause dispatch delays is an area of development that will assist in creating a more effective design revision studies.

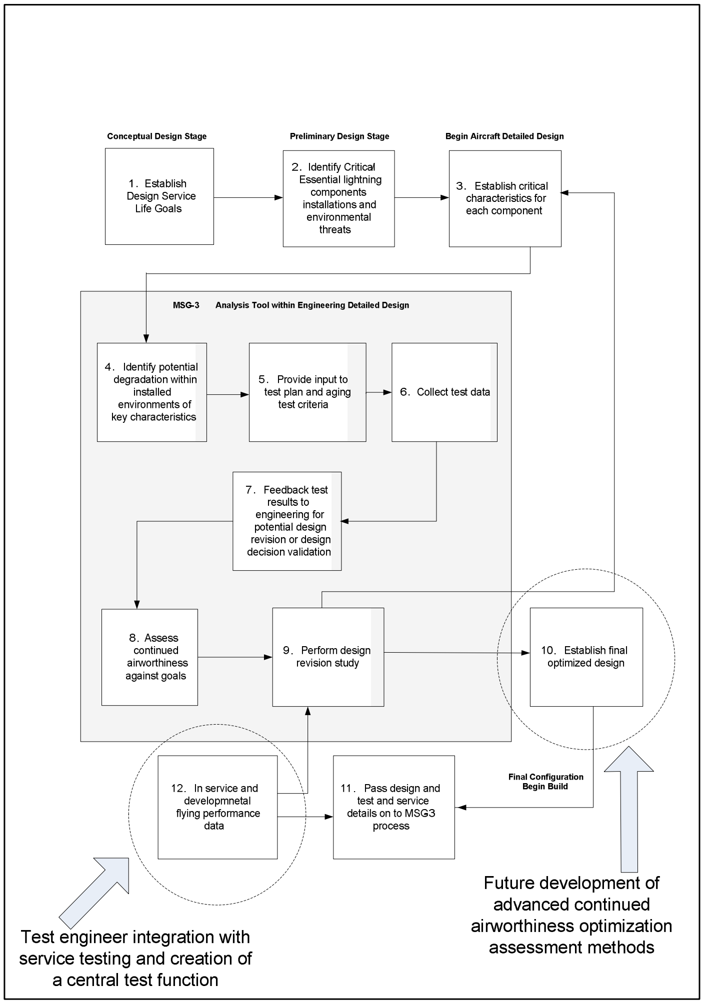


Figure 7-3 Other future expansions to the methodology

Design Guides

After completion of the case studies, it was determined that incorporation for some of the highlighted design considerations would be helpful additions to the OEM design guides. Further improvement to the methodology can be explored in development of improved design approaches that may be included in these guides. Part of the assessment performed within the methodology is to determine if a design is expected to last the life of the aircraft. This analysis can be developed further to include a design assessment committee to go beyond the evaluation of the design and tie into a design improvement and development committee. The assessment sheets can identify problems but do not include the potential solutions at this time. Further work on the concept of integrating the outcome of the methodology to already established aircraft design review processes is needed.

Dissemination of Lightning/HIRF Continued Airworthiness Knowledge

Finally, further work to incorporate continued airworthiness into standard aircraft design manuals, classroom text books, and industry design guides is required. This work expanded on designing an aircraft with the continued airworthiness of lightning protection designs as a focus in the process. Literature searches did not provide the kind of detailed design knowledge as presented in this body of work. The understanding of aircraft design phases and the proper place for incorporation of continued airworthiness design constraints is critical information to provide in state-of-the-art aircraft design teachings. Discovery of the importance of early goals and the effect of ignoring continued airworthiness concerns requires further transmission of the subject to the aircraft design community.

Integration of Test Data Development

Integration of test data for the design optimization of lightning protection continued airworthiness requires future development. Early establishment of the lightning protection components of choice should be evaluated based on testing. Test results may not provide the required information if the engineer in charge of lightning protection selection does not consider an organized process to input criteria into the test plan for continued airworthiness consideration. The engineer must inventory the known test results and categorize the tests to ensure that similar environmental threats are proposed for the test where known test results cannot be compared to the real installed environmental threats for the proposed application of the lightning protection. In some cases where the environmental threats are few, the degradation may be more readily predicted. In cases where multiple environmental threats exist simultaneously, more information may be required from the field. If the protection is exotic and never used before in the proposed application, more serious attention must be paid to the environment in which the new component will be installed. In this case, testing to failure may be a required alternative and certification testing may need supplemental test data.

7.4.4 Summary of Future Development Areas Identified by Case Studies and Research

Several areas of future development are identified through the research, validation and case studies. The following is a summary of some areas of study that require further work:

a. Further work on the format and content of the assessment sheets. Included in this work should be consideration for a database to manage the assessments.
b. Future work can be planned to determine if patterns of electrical bond degradation due to corrosion can be identified and a predictive methodology can be developed for corrosion effects on bonding characteristics.
c. Electrical bond degradation modeling can be investigated further. For the purpose of application of this methodology, electrical bond degradation models could not be found through literature searches in this industry. There may be electrical bond degradation models used for other purposes, but the author was unable to identify such a tool.
d. SAE Aerospace Recommended Practices (ARP) guidelines can be revised to include this thesis work and utilized more effectively within the proposed methodology. The SAE ARP documents that address lightning protection include a section on surveillance and maintenance of lightning protection. The author found these guidelines to be of little relevance to the concept of designing for continued airworthiness. Further development of these guidelines may be beneficial to create new knowledge and further the

emphasis of this methodology. Once revised, the SAE guidance can be referenced in the assessment sheets to tie the design criteria more closely to the SAE requirements.

e. The subjects of Electromagnetic Interference (EMI) or Electromagnetic Compatibility (EMC) protection were not included in this thesis. Investigation of the application of this methodology for the effects of EMI/EMC protection degradation is a development area; especially for future work in wireless control.

f. Lightning protection component assessment can be developed further. Work can be done on refinement of the assessment sheets and refinement of the application of the assessments. This thesis proposes one possible way to implement the assessment associated with the methodology. There are potentially more assessment ideas and other assessment procedures that can be developed to improve on the thesis proposal. One area of development may be in the creation of an assessment database. Also, the assessment sheets could consider the development of a risk index for lightning protection components installed within severe environments.

g. Lightning protection component installation zones do not exist as a design concept for aircraft development. This area of study could conceptualize a zonal system safety analysis for integrated systems that contain lightning protection. Current Enhanced Zonal Analysis Procedures (EZAP) performed to create maintenance and inspection instructions for Electrical Wiring Interconnection Systems (EWIS) mitigate smoke/fire events throughout all zones. However, lightning protection continued airworthiness is not part of that analysis process.

h. Relocation of a lightning protection component can be added as a possible outcome to the assessment. Further research into incorporation of component relocation into the methodology can be conducted.

i. Systems that are protected by lightning have associated criticality established by the Failure Mode, Effects, and Criticality Analysis (FMECA). Lightning protection components do not have specific criticality ratings. Investigation into whether the FMECA criticality can be integrated into the analysis sheets can be performed as future work. Perhaps ranking in terms of more critical designs could enhance the methodology. System Safety Analysis (SSA) procedures use a matrix of severity and probability (Catastrophic, Major, Minor FAR 1309). Safety assessments for 25.1309 failure hazard assessments also require additional assessment from the Design Assurance Level (DAL) to identify lightning protection component significance within the assessment. A convergence of these “safety” concepts may be investigated for applicability to the methodology.

j. Severity ratings for environments can be developed for lightning protection. Location, environmental threats and criticality of the installed components may be developed leading to a “Severity Rating” included on the assessment sheet.

k. Aircraft lightning protection is selected based on the electrical threat modeled for the location. Lightning zones on the aircraft identify the severity of the current/voltage and the probability of the strike to attach in that zone. The assessment model for lightning protection components may benefit from including the lightning zone in the assessment sheets. These sheets were revised during the case studies exercise to accommodate this feature. Further work on better use of this “electrical” threat rating in combination with the environmental ratings may produce a matrix that could improve the assessment outcomes.

l. Improvement of the methodology Step 7 titled, “Feedback test results to engineering for potential design revision or design decision validation” could be provided by inputs from a continued airworthiness advisory board. This concept was not proposed in the thesis. Further development of this process is needed. On this board specific expertise should be represented such as:
   1. Maintenance engineering
   2. Reliability engineering
   3. Production test engineering
   4. Electromagnetic engineering
   5. Certification engineering
   6. Developmental test engineering
   7. Wire design engineering
   8. Electrical bonding and Grounding (Earthing) engineering
   9. Material processes and technology engineering

   The board is responsible to the chief engineer for determining the most optimal solutions including cost, performance, and long term effectiveness of the designs.

m. Expansion of Step 9 in the methodology titled, “Perform design revision study” can more effectively assess revolutionary designs. Test data can include similar designs, simulated models, and developmental testing. This thesis discovered that past certified designs are sometimes selected for use on more advanced integrated aircraft without further testing or performance simulation completed. For this step in the methodology, the chief engineer needs to consider an organizational structure that can utilize exploratory testing as a way to determine design solutions even if the designed part has been successfully incorporated into past aircraft. Usually, this type of testing is called engineering tests or developmental testing. If the component has passed qualification testing for a previous aircraft application, further testing may not be required. For these exploratory test scenarios, the organization may be required to assemble exploratory test “development” even before the preliminary design stage of the project. This kind of innovation is needed to avoid design delays, progress interruptions and retests for designs that were imagined but not produced. Further study of this idea should be completed.

n. Creation of a means for assessing the design is required in Step 9 of the proposed methodology. This is an area of future work required to ensure that appropriate balance is achieved in making the decisions. A gathering of data associated with continued airworthiness of lightning protection would be helpful in supporting this expansion. For many aircraft development programs reliability data is used to determine where certain systems should concentrate efforts for improvements. In the case of lightning protection, reliability data is most likely not collected through this reliability system. Since lightning protection is mostly passive, indications of lightning protection failures are difficult to isolate. Operational impacts to airlines related to lightning strikes that cause dispatch delays is an area of development that will assist in creating a more effective design revision study.

o. One simple modification to the assessment sheet is the incorporation of a materials chart. Further research should be performed on creation of an active assessment system that can reject certain combinations of design and environment given the materials and environmental threats.

p. A method for determining corrosion severity and the relationship between corrosion in a conductive joint and its relation to the conductivity is required future work. For this, work is required to establish the most common materials in the conductive interface such as aluminum interface with titanium and then applying a controlled amount of salt spray to the joint while recording resistance of the joint as the corrosion increases. Tables can be generated with this information and a family of exposure levels can also be determined as a variable and recorded for each scenario. These tables should be tested with multiple test cases of the same material and moisture exposures to evaluate reproducibility of the results. Once tables of this nature are established, the information can be used in determining the expected outcome of certain electrically conductive interfaces within specific environments. These tables can also represent the impact to long term conductivity for different sealant methods and sealant types.

q. The manufacturers preferred parts list needs to interface with this methodology. A revision of the methodology to directly tie the environmental threat design criteria and the approved parts list process into assessment sheets could provide an improvement to the methodology.

r. Additions to OEM Design Manual are necessary using the findings of this thesis.

s. The methodology can be improved by expanding the nature of the assessment to also include the revised design recommendations. In that case the review committee envisaged in this methodology would be tasked to go beyond the evaluation of the design and be made directly responsible for design improvement and development. Currently, the assessment sheets can identify problems, but do not include the potential solutions. Further work on this concept is needed.

t. An improvement to the assessment sheets may be to test the component resistance at time of installation to establish an “as installed” value for use in future evolution of the methodology and document these values in the assessment sheets (or future database). It is important to install the lightning protection bonds properly. The current systematic approach proposed in this thesis does not include the examination of the installation process to ensure continued airworthiness of the installation is secured. This deeper involvement in the design engineering of components can be future work associated with this thesis.

u. More future work can be performed on the expansion of design processes to include continued airworthiness of lightning protection. This concept may also be adaptable to other disciplines. The importance of establishing early goals was highlighted for lightning protection in this thesis. The inclusion of continued airworthiness within these early goals should be investigated for potential advantages to other disciplines.

7.5 Contributions to Knowledge

A significant contribution to knowledge created through this work is the potential for the methodology to be applicable to other design approaches. This expands the impact of the methodology to other disciplines such as flight controls, avionics and structural design processes. The expansion of the methodology creates a translational relationship of the learning to applications beyond the objectives of this work.

Specific knowledge contributions in the area of lightning protection design include revision of the way aircraft designers approach lightning protection design data gathering. The performance of lightning protection on an aircraft is not simply a certification requirement, but the contribution to knowledge on this subject highlights that lightning protection designs also require a continued airworthiness robustness that cannot be left to chance any longer. Instead, incorporation of the continued airworthiness design constraint will revise permanently, the way lightning protection is designed.

In order to make this design methodology attainable, process changes are required for data collection, distribution, and utilization. The assessment sheets that were designed to demonstrate the methodology can be revised, enhanced, or even replaced with an interactive computing system. Use of assessment sheets was appropriate to demonstrate the methodology within the case studies; however, a database may be much more useful and effective in dealing with large amounts of data distributed over many specialist engineering groups and suppliers.

The contribution to knowledge in demonstrating the methodology with the case studies were the association of electrical bonding and grounding knowledge to the lightning protection continued airworthiness. Most bonding and grounding requirements ensure that an electrical bond is attained at the time of the aircraft assembly. This approach does not concern itself with continued availability of the bond over the life of the aircraft. Since the electromagnetic compatibilities and electrical bonding and grounding skills are departmentalized, the assessment sheets provided evidence that cross examination between these skill sets would benefit the final design outcome. Given an understanding of the continued airworthiness design criteria and combining this understanding with a design methodology change; the outcome has been proven by the case studies to be greatly beneficial to aircraft design robustness. Another contribution to knowledge was the differences between lightning protection design time phase in a development program and the maintenance program development time phase. These two design processes are not interfaced at a point in the design development to appropriately revise poor long term performing designs. Timing of the MSG-3 analysis that is used to create the initial minimum scheduled maintenance program is much too late in the design process to be an appropriate tool for optimizing designs.

In order to leverage the knowledge gained by this body of work, one must revise the aircraft design process to consider lightning protection continued airworthiness early in the development phase. Lightning protection failure and its consequences in the case of a lightning event may be included within the particular risk assessments of FAR/JAR 25.1309 as a way to capture the aircraft operational impact of the failure. This however may not provide all the lightning protection schemes needed to process through the methodology since the process is event and system centric. Lightning protection component critical characteristics can be determined earlier in the design process if a system is created to account for this revision. Current design processes do not seem to apply enough attention to the determination of materials and finishes ability to maintain good long-term electrical bonds early in the development process. As an example, the proposed methodology has the establishment of critical characteristics for each component at the beginning of the detailed design stage. Step three in the methodology is where the critical characteristics such as the material and finish of lightning shield within looms are determined. This is proposed to be the same as it is today, however further consideration should be provided to the possibility that the critical characteristics in step three be moved to step two at the preliminary design stage where identification of critical and essential lightning protection components in the installed environments are provided by the design team. This may benefit the methodology further to provide visibility of the importance of the materials and finishes selected earlier in the program. An example of this may be use of a tin shield on a wire loom outside the pressure vessel. The resistance of the indirect protection provided by tin shields is well established in the industry; however, there have been findings of degraded tin shields outside the pressure vessel. If this tin shield is chosen at the beginning of detailed design as proposed in the new methodology, it may be too late to revise the shield without major impact to the connector back shell in which the shield interfaces to provide protection to the loom. Changes in wiring designs at the detailed design phase of a program can have negative impacts on the suppliers and component manufactures.

Certification Aspects

Consideration of the lightning protection way forward to certification brought to light new challenges for what is required to develop better performing designs. Past processes evaluated lightning threats in aircraft lightning zones and determined the appropriate protection to protect the aircraft at the time of initial flight of the aircraft. While completing the case studies, it was discovered that the selection of lightning protection schemes may be altered if consideration for FAA FAR 25.1529 (Instructions for Continued Airworthiness) is included in the protection design selection criteria at the start of the design development. Consideration of this regulatory requirement will impact lightning protection designs in a way that was not performed on past aircraft design programs. Requirement for sealants, composite structure assemblies, electrical bond paths and long term availability of these lightning protection components as installed on the aircraft will generate differences in the design outcome, different than those produced using past methodologies. Early establishment of the lightning protection components of choice should be evaluated based on testing beyond the qualification testing that is already in place. Tests for the aging effects of environment are extremely useful to determining good long-term performing components. Test results may not provide the required information if the engineer in charge of lightning protection selection does not consider an organized process to input criteria into the test plan to ensure adequate test data results that are needed for optimum implementation of the methodology. The engineer must inventory the known test results and categorize the tests to ensure that similar environmental threats are proposed for the test that would be expected on the aircraft for an extended period of time. Some parts are exposed to salt spray for 50 hours. These tests are to qualify the part for initial installation on the aircraft. Other qualification tests may take 500 hours of salt spray. It is the choice of the test plan manager to determine applications of parts and propose appropriate tests for the parts with an understanding of the ultimate application and location of the part. These decisions are not currently tied to a closed-loop assessment process like that proposed in this body of work. Without the application of a methodology such as the one proposed here, known test results cannot be compared to the real installed environmental threats for the proposed application early in the design phase of the development program. In some cases where the environmental threats are few, the degradation may be more readily predicted and test results may not be as significant to the final outcome. In cases where multiple environmental threats exist simultaneously, more information may be required from other components that are already installed on existing aircraft after a long period of duty. If the protection is exotic and has never been used before in the proposed application, more serious attention must be paid to the environment where the new component will be installed. In this case, testing to failure may be a required alternative and certification testing may not be adequate. These understandings are contributions to knowledge that drive this improved design approach. The association of the design threats contained in the case studies and specific lightning protection components information regarding the installation techniques yielded conclusions within the assessment sheets that provide further design engineering guidance. Combining this assessment with service experience is even more impactful to improving the design.

Data Gathering

Further contribution to knowledge relates to the tedious nature of the data gathering. For this methodology to run smoothly, a data gathering process needs to be integrated into the design development activities. Information gathering for the case studies was very tedious and demonstrated that an integrated process for including the lightning protection design continued airworthiness into the development phase of an aircraft design program would be less tedious. Gathering data at the beginning of the development program would allow the committee performing the assessment to influence the design at a more effective point in the program development phase. The aircraft design process is iterative in nature. The use of the assessment sheets in the case studies demonstrated that feedback from design assessments is important especially when a system is found to be inadequate for the life of the aircraft. An example of this was included in the case where a connector design was found to be inadequate for the application outside the pressure vessel.

Inadequacy of FHA

The case studies demonstrated that the use of a failure hazard assessment to determine appropriate lightning protection schema is not enough to address the lightning protection design robustness over the life of the aircraft. The concept of design assurance levels was introduced within the case studies that assisted with the necessary categorizing of lightning protection systems. An entire section of the Chapter 5 was dedicated to the concept of safety and the different processes associate with design assurance. This may be an area where further development can be conducted to further rationalize which lightning components are the most critical and should be taken through the design methodology. After review of the EMC test reports generated at the time the aircraft was designed, it was noted that the continued airworthiness of the EMC protection under test was not included as a category within the EMC test report.

Final conclusions determined that the early development of the aircraft used in the case studies would have benefited from this methodology. The design approach used to develop the aircraft evaluated in the case studies produced designs that require scheduled maintenance since the design robustness was not found to be adequate enough to perform its intended function adequately over the life of the aircraft. To some degree this can be written off as "hind-sight" but the knowledge gained in this body of work suggests that a different design solution may have been chosen given the advantages of the methodology in identifying performance issues at an early stage in the design cycle. This can also be correlated to the lack of an integrated design process such as the one hypothesized by this work.

Contribution to Knowledge High Points

This endeavor of work led to the collection of information under one idea that has never been assembled before outside this thesis. The years of literature searches has not produced any evidence that this idea is part of any established current knowledge base. Evidence to the innovation of this design methodology is the patent application of the methodology to protect the value of the idea. With this new knowledge established as valid and effective by several case studies presented within this thesis; implementation of the methodology on a future development program is likely. The thesis discovered issues with certification methods that need understanding, and generated efficiencies given certain practices recommended in the thesis that can be leveraged to produce more superior results on an aircraft development program. Some of the many contributions to knowledge are as follows:

1. Revision of design practices and organizational structure of a design program.
2. Contributions to general aviation knowledge base through production of technical papers on the subject during the five years of thesis development.
3. Brought better understanding of test data relevance and collection process improvements for information gathered by test including expanding test results reviews within the methodology to accept input from other projects and exploratory initiatives

4. Discovered that performance goals must be more effectively tied to continued airworthiness. Most current aircraft certifications rely on past practices that may result in failure of performance goals in the long term.
5. Discovered the benefits of considering alternative components early in the program. Implementation of components used on past programs may not perform as well as the new program goals desire.
6. Discovered a way forward to avoid late findings impacting the program and potentially causing development schedule delays. The methodology suggests that early assembly of operational performance data for lightning protection components should be performed and used in design decision making.

The case studies demonstrated that the earlier design approach used to develop the aircraft in the case studies could be optimized with a different approach to continued airworthiness. This can be correlated to implementation of an integrated design process such as the one hypothesized by this thesis.

Improvements to the methodology can be performed as future development for improving aircraft designs. Key to the future work is assessment to determine if a design is expected to last the life of the aircraft leveraging performance data. Further work on implementing the concept is needed.

Chapter 8 Summary, Conclusions, and Further Work Summary

The following is a condensed list of findings, discoveries and further work associated with this body of work. These points address the highlights of the work and provide quick reference to the accomplished work and the proposed follow-on work.

8.1 Conclusions

Effectiveness of the Methodology

1. The aim of this body of work was to determine a way to include continued airworthiness into the design of lightning protection. The methodology proved to work effectively to include continued airworthiness into the design process.
2. The versatility of the methodology was proven by use of several case studies. The case studies proved applicability of the methodology on substantially different lightning protection components. The proposed methodology proposed is adaptable to multiple lightning protection design component types.
3. The methodology provides a way to assess improving an existing design vs. developing a new design. The addition of multiple test cases produced more effective results in this thesis. Cases were selected with composite and metallic designs to demonstrated differences.
4. Further technical work on lightning zone correlation to the continued airworthiness of lightning protection components can enhance the methodology. Severity indexes can be created including lightning strike zone severity and environmental conditions. Details regarding the aircraft lightning environment, aircraft environmental threats, and associated details of the wire installations criteria in vibration, temperature, and moisture can generate better analysis resulting in more effective long lasting designs.

5. The case studies concluded that the methodology can be effectively applied to new technologies.
6. Equipment criticality was explored. The methodology was revised to include the Design Assurance Levels for the lightning equipment. The difference between the criticality determined by the FAR 25.1309 safety analysis and the safety determinations through the AC20-136 Design Assurance Level process were clarified. Findings were provided that demonstrated how a system considered non-critical by the FAR 25.1309 safety analysis could be elevated to a hazardous or catastrophic level failure by AC20-136. This observation emphasized the need for understanding the electromagnetic perspective for lightning protection safety determination Also, direct application of the systems safety analysis may produce an incorrect lightning protection components classification. This could drive incorrect protection applications. The subject of new or significantly modified systems and its impact to the methodology was described.
7. Design assurance levels were introduced within the case studies that assisted with the necessary categorizing of lightning protection systems in the application of the methodology. The case studies demonstrated that the failure hazard assessment is not enough to address the lightning protection design long-term robustness. An entire section of the case studies was dedicated to the concept of safety and the different processes associate with design assurance.
8. Design solutions for the expected "standoff" voltage that control equipment experience at the junction from outside the equipment to the internal equipment control electronics are required as an input to the methodology. Working with this requirement, designers establish electrical bonding schemes to ensure that the required voltages are within the specified levels.
9. Current paths were added to the methodology procedure. Electrical bond paths for lightning protection installations were described in detail. During a lightning strike event, lightning current travels along the aircraft structure inducing current on wire installations to the attached equipment.
10. The case studies proved that both direct and indirect lightning strike threats can be addressed by the methodology.

Methodology Improvement

1. A revision of the methodology to directly tie the environmental threats design criteria and the approved parts list process into the methodology and assessment sheets is also a suggested improvement.
2. Incorporation of a materials chart is a suggested methodology improvement.
3. An assessment committee procedure would improve the methodology. Part of the design assessment is to determine the design long-term viability. The methodology can be developed further to include a design assessment committee. Further work on this concept is needed.
4. A predictive methodology to model the corrosion effects on electrical bonding characteristics degradation should be investigated. This could be a further expansion of this area of research and development work.

Design benefits

1. Design methods for continued airworthiness can produce better performing designs if a proactive design technique such as the one proposed by this thesis is applied for lightning component continued airworthiness.

2. Design goals must incorporate effective recognition of continued airworthiness criteria and leverage performance data.
3. The ability to share data, exchange ideas, and apply test results leads to better designs. Design group integration of diverse design disciplines is an effective way to implement the methodology.
4. Designs that are adopted from past certification programs may be an acceptably low risk alternative to creating new designs but may also produce sub-optimal designs if not evaluated in a manner consistent with the methodology proposed.
5. The concept of primary and secondary structure protection benefited the design assessment and was used in the case studies to organize the design process.
6. Research identified that a study by the National Institute of Aviation Research determined that aircraft which are fully protected from lightning adverse effects had a significantly lower percentage of electrical failures. This discovery leads to the conclusion that the methodology demonstrated in this case studies would bring a significant value to the aircraft design process.
7. The association of the design threats to the lightning protection components and installation techniques yielded further design engineering guidance. Combining the assessment with service experience improved the design outcome.

Design Method Improvements

1. More research is required to adjust aircraft design handbooks. Knowledge gained from this thesis must be included in relevant design manuals. The AIAA lightning protection design book can benefit from this knowledge.
2. The criticality of electrical bonding on aircraft was evaluated by this work. Literature searches resulted in discovery of an electrical bonding design guide developed by the OEM. Incorporation of the results of this thesis could be provided as a revision to enhance the bonding requirements practices developed for the new aircraft design processes discussed in this thesis. Reference to this design guide is included in the case studies. The importance of an electrical earthing design guide was highlighted and principles of the design guide were included in the case studies exercise.
3. For early aircraft designs, sealant was not deemed necessary, especially in applications where equipment may require removal for maintenance or overhaul. Through research of the case studies, it was discovered that sealant applications are an important part of lightning protection continued airworthiness. Understanding appropriate applications of sealants, appropriate types of sealants and the relationship to the continued airworthiness of the installation was achieved through the case studies exploration of information gathered through a literature search. As a result of this learning, the analysis sheets that drive the assessments for continued airworthiness were revised to include a category for the sealant application and type.
4. Cleaning methods associated with preparation of electrical bonding installations were explored and included within the analysis. Specific electrical bonding information regarding the aircraft in the case studies was acquired through literature searches and is included within the case studies.
5. Information gathering for the case studies demonstrated that an integrated process for including the lightning protection design continued airworthiness into

the development phase of an aircraft design program would be far more efficient than gathering the required data later in the development program.

6. The case studies demonstrated that the earlier design approach used to develop the aircraft can be improved if this methodology is applied. This can be accomplished using an integrated design process such as the one demonstrated by this body of work.
7. Inclusion of EMC test reports is an improvement to the design methods used in current practice. After review of the EMC test reports generated at the time of the aircraft design it was noted that the continued airworthiness of the EMC protection under test was not included as a category within the report structure.

Maintenance Program Benefits

1. Lightning protection maintenance programs can be optimized if the designs are influenced by continued airworthiness data before they are final.

Service Data Enhances Designs

1. Gathering and leveraging service experience within a design community requires a formal methodology and embrace from the design community leadership. This service data is valuable information if used in a design methodology such as the one proposed in this thesis.
2. Lightning protection degradation issues must be captured in a database and used for future designs consistent with the findings in this thesis.

Certification Impacts

1. The methodology modifies past certification practices. For lightning protection design, multiple paths through to certification were demonstrated by this thesis.
2. Certification practices that use similarity of components on other certified aircraft configurations must be checked for service performance. Similarity may be used to adopt the design however, long-term effectiveness cannot be assumed if the components are not tested on an active aircraft before similarity is used as a reason to adopt the design. Caution should be applied here since many lightning protection components operate passively.
3. It was discovered that the lightning certification process has a large impact on the lightning protection design development. Certification process research on the methodology impact was included in the case studies. In cases where components were certified on previous aircraft development programs, additional design assessment may not be necessary. This could lead to sub-optimal designs and perpetuation of a lightning design feature that could be improved for continued airworthiness if the methodology proposed in this body of work was used. The methodology can be used for both new and reconfigured or derivative aircraft.

Maintenance Requirements Integration

1. Inclusion of maintenance requirements can be added to the methodology to create optimized designs. This was not considered in the early version of this work but was learned as the work matured. At later stages of the case studies development, the incorporation of maintenance as an alternative to the redesign of a lightning protection component was included as part of the methodology and part of the design assessment sheets. The maintenance program is generally determined after the designs have been completed.

2. Early incorporation of the maintenance program requirements during the design phase can further optimize the design for continued airworthiness and can mitigate maintenance costs later in the life of the aircraft.
3. It was also determined that lightning inspection instructions provide a good summary of the design features that an OEM consider important. Research into the OEM maintenance manual and across several different aircraft maintenance manuals provided information that was included in the case studies to define the general principles associated with aircraft lightning protection inspections. This knowledge is a great enhancement to understanding continued airworthiness issues associated with damage after a lightning strike.
4. Lightning protection maintenance can be improved with this design assessment methodology. Changes to designs may be recommended and subsequently evaluated for practicality by use of a feedback methodology added to the early version of the methodology proposed prior to completion of the case studies.

Accidents and Incidents Due to Lightning Enhances Understanding

1. Aircraft crash reports from legitimate regulatory investigations related to lightning events were included in the case studies. These investigations led to understanding how lightning can affect the continued safe flight and landing of an aircraft and also provide information on the importance of maintaining lightning protection. In one case the evidence of missing or improperly installed bond jumpers (earthing wires) led to understanding that continued airworthiness of aircraft against the effects of poor designs, is a key design specialty. In the lightning strike examples, both passengers and flight crew were harmed by a hard landing due to reduced controllability of the aircraft after the lightning strike and subsequent collapse of the landing gear. In another case, lightning was suspected to have caused a complete electrical failure. Revision to the aircraft flight manual has been recommended to inspect the aircraft after lightning strike when loss of electrical power results from the strike.

Assessment Sheet Improvements and Benefits

1. Analysis work sheets are a way to implement integration of the methodology into a design community. These analysis sheets need to remain flexible to account for potential expansion of the analysis process and incorporation of other design concerns not identified in this thesis.
2. The lightning protection components assessment model was improved by including the lightning zone in the assessment sheets. Lightning zones on the aircraft identify the severity of the current and probability of the strike. The sheets were revised during the case study exercises to add this feature.
3. The assessment sheets assisted with the effort of integrating information and design details. Some of the required details for the assessment sheets are in the drawings on several sheets. The case studies demonstrated the importance of data integration within the design process.
4. The assessment sheets can identify problems but do not include the potential solutions. This should be developed further.
5. The analysis sheets are designed to address both federate designs and highly integrated designs. They can assist with the cross-organizational support necessary to succeed at designing highly integrated systems.

6. The use of the assessment sheets in the case studies demonstrated that feedback from design assessments is important, especially when a system is found to be inadequate for the life of the aircraft. An example of this was included in the case where a connector design was found to be inadequate for the application outside the pressure vessel.
7. Testing the component resistance at the time of installation may be helpful to add to the assessment sheet. These bonds are important to be installed properly at the time of aircraft assembly. Current systematic approaches must include the examination of the installation process or design to ensure continued airworthiness of the installation is maintained.

Important Case Study Findings

1. The case studies identified the association of electrical bonding and grounding knowledge to the lightning protection continued airworthiness. Since the electromagnetic compatibilities and electrical bonding and grounding skills are departmentalized, the assessment sheets provided evidence that cross examination between these two skill sets would benefit the final design.
2. For highly integrated aircraft, the lightning protection continued airworthiness includes many more systems for which the assessments can be applied.

8.2 Recommendations and Further Work

The following recommendations are the top items of most impact for future work:

- Develop an automated analysis tool for assessing lightning protection continued airworthiness. Automate the assessment criteria such as the galvanic tables and electrical bond degradation models due to corrosion.
- Design a database tool with algorithms to combine design data with environmental threat information and establish robustness ratings based on the models.
- Design a tool to incorporate all known evidence of lightning protection degradation and location on the aircraft. Use this tool to validate application of known components in alternative locations and as a predictive tool for optimizing bond design placements on the aircraft.
- Develop a trade study for evaluating the lightning protection components and provide a design team integration solution for the trade study conclusions to be applied to new designs or design improvements.

Appendix A – Terms Used in Certification of Systems

Term	Description
Airworthiness	The condition of an item (aircraft, aircraft system, or part) in which that item operates in a safe manner to accomplish its intended function.
Analysis	An evaluation based on decomposition into simple elements.
Approval	The act of formal sanction of an implementation by a certification authority.
Approved	Accepted by the certification authority as suitable for a particular purpose. (CAO)
Assessment	An evaluation based upon engineering judgment.
Assumptions	Statements, principles and/or premises offered without proof.
Assurance	The planned and systematic actions necessary to provide adequate confidence that a product or process satisfies given requirements. (RTCA DO 178B)
“At Risk” Time	The period of time during which an item must fail in order to cause the failure effect in question. This is usually associated with the final fault in a fault sequence leading to a specific failure condition.
Authority	The organization or person responsible within the State (Country) concerned with the certification of compliance with applicable requirements.
Availability	Probability that an item is in a functioning state at a given point in time.
Certification	The legal recognition that a product, service, organization, or person complies with the applicable requirements. Such certification comprises the activity of technically checking the product, service, organization or person, and the formal recognition of compliance with the applicable requirements by issue of a certificate, license, approval, or other documents as required by national laws and procedures.
Certification Authority	Organization or person responsible for granting approval on behalf of the nation of manufacture.
Common Cause	Event or failure which bypasses or invalidates redundancy or independence.
Common Cause Analysis	Generic term encompassing Zonal Analysis, Particular Risks Analysis and Common Mode Analysis.
Common Mode Failure	An event which affects a number of elements otherwise considered to be independent.
Complexity	An attribute of systems or items which makes their operation difficult to comprehend. Increased system complexity is often caused by such items as sophisticated components and multiple interrelationships.
Compliance	Successful performance of all mandatory activities; agreement between the expected or specified result and the actual result.

Term	Description
Component	Any self-contained part, combination of parts, subassemblies or units, which perform a distinct function necessary to the operation of the system.
Conformity	Agreement of physical realization of the item with the defining document.
Criticality	Indication of the hazard level associated with a function, hardware, software, etc., considering abnormal behavior (of this function, hardware, software, etc.) alone, in combination or in combination with external events.
Defect	State of an item consisting of the non-performance of specified requirements by a characteristic of the item. A defect may, but need not, lead to a failure.
Demonstration	A method of proof of performance by observation.
Derived Requirements	Additional requirements resulting from design or implementation decisions during the development process. Derived requirements are not directly traceable to higher level requirements; though derived requirements can influence higher level requirements.
Design	The result of the design process.
Design Process	The process of creating a system or an item from a set of requirements.
Development Assurance	All those planned and systematic actions used to substantiate, to an adequate level of confidence, that development errors have been identified and corrected such that the system satisfies the applicable certification basis.
Development Error	A mistake in requirements determination or design.
Error	(1) An occurrence arising as a result of an incorrect action or decision by personnel operating or maintaining a system. (JAA AMJ 25.1309) (2) A mistake in specification, design, or implementation.
Event	An occurrence which has its origin distinct from the aircraft, such as atmospheric conditions (e.g., wind gusts, temperature variations, icing, lightning strikes), runway conditions, cabin and baggage fires. The term is not intended to cover sabotage. (JAA AMJ 25.1 309) Note: This definition, as it is stated here, describes an "External Event". There are other uses of "event" that cover other aspects (e.g., FTA events).
Exchanged Function	Refers to interdependencies between functions.
Exposure Time	The period of time between when an item was last known to be operating properly and when it will be known to be operating properly again.
Failure	A loss of function or a malfunction of a system or a part thereof. Note: This differs from the ARP 4754 definition and conforms to the AC/AMJ 25.1309 definition.

Term	Description
Failure Condition	A condition with an effect on the aircraft and its occupants, both direct and consequential, caused or contributed to by one or more failures, considering relevant adverse operation or environmental conditions. A Failure Condition is classified in accordance to the severity of its effects as defined in FAA AC 25.1309-1A or JAA AMJ 25.1309.
Failure Effect (FE)	A description of the operation of a system or an item as the result of a failure; ¡.e., the consequence(s) a failure mode has on the operation, function or status of a system or an item.
Failure Mode (FM)	The way in which the failure of an item occurs.
Failure Rate	The gradient of the failure distribution function divided by the reliability distribution function at time t. If the failure distribution function is exponential, the failure rate is constant and the failure rate can be approximately calculated by dividing the number of failures within a hardware item population, by the total unit operating hours. Note: Failure rate could also be expressed in terms of failures per flight hour or per cycle.
Fault	An undesired anomaly in an item or system.
Functional Hazard Assessment (FHA)	A systematic, comprehensive examination of functions to identify and classify Failure Conditions of those functions according to their severity.
Guidelines	Recommended procedures for complying with regulations.
Hardware	An object that has physical being. Generally refers to LRUs, circuit cards, power supplies, etc.
Hazard	A potentially unsafe condition resulting from failures, malfunctions, external events, errors or a combination thereof.
Implementation	The act of creating a physical reality from a specification.
Independence	(1) A design concept which ensures that the failure of one item does not cause a failure of another item. (Derived from JAA AMJ 25.1309) (2) Separation of responsibilities that assures the accomplishment of objective evaluation.
Inspection	An examination of an item against a specific standard.
Integration	(1) The act of causing elements of an item to function together. (2) The act of gathering a number of separate functions within a single implementation.
Item	One or more hardware and/or software elements treated as a unit.
Latent Failure	A failure which is not detected and/or annunciated when it occurs.
Malfunction	The occurrence of a condition whereby the operation is outside specified limits.

Term	Description
Novelty	Applicable to systems using new technology and to systems using a conventional technology not previously used in connection with the particular function in question.
Preliminary System Safety Assessment (PSSA)	A systematic evaluation of a proposed system architecture and implementation based on the Functional Hazard Assessment and failure condition classification to determine safety requirements for all items.
Product	An item generated in response to a defined set of requirements.
Redundancy	Multiple independent means incorporated to accomplish a given function.
Reliability	The probability that an item will perform a required function under specified conditions, without failure, for a specified period of time.
Requirement	An identifiable element of a specification that can be validated and against which an implementation can be verified.
Risk	The frequency (probability) of occurrence and the associated level of hazard.
Segregation	The maintenance of independence by means of a physical barrier between two hardware components.
Separation	The maintenance of independence by means of physical distance between two hardware components.
Similarity	Applicable to systems similar in characteristics and usage to systems used on previously certified aircraft. In principle, there are no parts of the subject system more at risk (due to environment or installation) and that operational stresses are no more severe than on the previously certified system.
Software	Computer programs, procedures, rules, and any associated documentation pertaining to the operation of a computer system.
Specification	A collection of requirements which, when taken together, constitute the criteria which define the functions and attributes of a system, or an item.
System	A combination of inter-related items arranged to perform a specific function(s).
System Safety Assessment (SSA)	A systematic, comprehensive evaluation of the implemented system to show that the relevant safety requirements are met.
System Safety Assessment Process	The complete process applied during the design of the system to establish safety objectives and to demonstrate compliance with FAWJAA 25.1309 and other safety related requirements.
Validation	The determination that the requirements for a product are sufficiently correct and complete.
Verification	The evaluation of an implementation to determine that applicable requirements are met.

Appendix B – Terms Used in Electrical Bonding

Term	Description
Case Ground	Current return path through equipment mounting surface.
Chassis Ground	A bond wire connection from an equipment case through the electrical connector to structure.
Current Return Ground	A current-carrying path established between the “ground side” of the circuit of an electric or electronic device and the primary structure.
Designated Bond	Electrical bond of such importance that its maximum allowable resistance and design requirements must be specified on engineering drawings and verified after each assembly of the bond by measurement.
Designated Ground	An electrical ground of such importance that the maximum allowable resistance and other requirements are specified in engineering drawing. All designated grounds are checked 100 percent during production.
Discontinuity	A lack of electrical continuity between joined conductive objects.
Driven Rivet Bond	A bond formed between non-conductive finished pieces of metal structure by three or more driven rivets without faying surface preparation.
Dual Ground	Connection technique which provides two attachments of a current return to structure.
Dual Terminated Ground	See dual ground.
Electrical Bond	A fixed union between two objects that result in electrical conductivity between the objects.
Electrical Bonding	The process of connecting together electrically two or more conductive objects.
Electrical Ground	An electrically conductive return path from equipment to structure.
Electromagnetic Compatibility (EMC)	The capability of equipment or systems to be operated in their intended operational environment at designed levels of efficiency without causing or receiving degradation owing to unintentional electromagnetic compatibility.
Electromagnetic Interference (EMI)	Conducted induced or radiated electrical energy that creates an undesirable response in the operation of electrical or electronic equipment.
Electromagnetic Pulse (EMP)	An extremely short, intense burst of radio frequency energy from a nuclear explosion.
Fault	An undesired electrical occurrence. A reduction of or complete loss of isolation between circuits at different potentials.
Fault Current	A higher than normal current which flows in a circuit due to an electrical fault brought on by material, equipment or personnel failure.

Term	Description
Faying Surface	A conductive surface prepared to fit against a second conductive surface such that an electrical bond results from the physical contact.
Fire/Explosion Hazard Area	An equipment location or work area that may contain be contaminated with a combustible material or vapor.
Flammable Leakage Zone	An area where flammable liquid or vapor can be expected to occur due to single failure or leakage during operation.
Ground Fault	An inadvertent connection of a power circuit to structure, due to wiring or equipment failure.
Grounding (Earthing)	The process of providing an electrical circuit return path to primary structure. Also, the process of providing an electrical connection from the structure or airframe to earth.
Inherent Bond	Conductive metallic parts which are permanently assembled such that a low resistance junction occurs. Examples include parts joined by welding, brazing, sweating, swaging, soldering etc., and major metal fusion such as metallic structural members secured by large numbers of fasteners.
Interface	The surface area where two parts are joined.
Jumper (bond jumper or earth wire)	A short wire assembly, metal braid or metal strap used to provide electrical continuity between two conductive objects.
Lightning Strike Attachment	Being contacted by a lightning current discharge to vehicle.
Non-designated Bond	Electrical bond whose requirements are not specified on engineering drawings. For such a bond the electrical conductivity requirements are not critical.
Precipitation Static (P-Static)	Electrical interference caused by static electricity leaking off a vehicle. The source of the interference is corona discharge which occurs at sharp edges, points and tips of the vehicle structure due to the large charge density at these points.
Primary Structure	The major metallic portion of the vehicle which carries primary structural loads. Members secured by less than twelve structural-type fasteners are not normally considered as such a structure.
Secondary Structure	That portion of the vehicle which does not contribute to structural strength. Examples include accessory mounting brackets, panels, panel supports, equipment racks and seat tracks.
Static Bond	A bond between an otherwise isolated conductive object and the primary structure to prevent accumulation of electrostatic charge(s) caused by gases or fluids in motion.
Static Ground	An electrically conductive path from the vehicle to earth to dissipate electrostatic charges accumulated and to prevent accumulation of electrostatic charge while the vehicle is at rest.
Transient	A short-duration voltage or current pulse.
Voltage Reference Plane	The primary structural current return path for electrical power sources.

Appendix C - Critical Lightning/HIRF Protected Systems Qualification Methods

Proprietary data retained. Contact Author

Appendix D – Essential Lightning/HIRF Protected Systems Qualification Methods

Proprietary data retained. Contact Author

Appendix E – Definition of terms used in the Development of Lightning Direct Effects Protection

Term	Description
Attachment Point	A point of contact of the lightning flash with the aircraft.
Breakdown	The production of a conductive ionized channel in a dielectric medium resulting in the collapse of a high electric field.
Dwell Point	A lightning attachment point.
Dwell Time	The time that the lightning channel remains attached to a single spot on the aircraft.
External Environment	Characterization of the natural lightning environment for design and certification purposes.
First Return Stroke	The high current surge that occurs when the leader completes the connection between the two charge centers. The current surge has a high peak current, high rate of change of current with respect to time (di/dt) and a high action integral.
Flashover	This term is used when the arc produced by a gap breakdown passes over or close to a dielectric surface without puncture.
Leader	The low luminosity, low current precursor of a lightning return stroke, accompanied by an intense electric field.
Lightning Channel	The ionized path through the air along which the lightning current pulse passes.
Lightning Flash	The total lightning event. It may occur within a cloud, between clouds or between a cloud and ground. It can consist of one or more return strokes, plus intermediate or continuing currents.
Lightning Strike	Any attachment of the lightning flash to the aircraft.
Lightning Strike Zones	Aircraft surface areas and structures classified according to the possibility of lightning attachment dwell time and current conduction.
Reattachment	The establishment of new attachment points on the surface of an aircraft due to the sweeping of the flash across the surface of the aircraft by the motion of the aircraft.
Restrike	A subsequent high current surge attachment, which has a lower peak current, a lower action integral, but a higher di/dt than the first return stroke. This usually follows the same path as the first return stroke, but may reattach to a new location.
Stepped Leader	See leader.
Swept Leader	A lightning leader that has moved its position relative to an aircraft, subsequent to initial leader attachment, and prior to the first return stroke arrival, by virtue of aircraft movement.
Swept Channel	The lightning channel relative to the aircraft, which results in a series of successive attachments due to sweeping of the flash across the aircraft by the motion of the aircraft.
Zoning	The process (or the end result of the process) of determining the location on an aircraft to which the components of the external environment are applied.

Appendix F – New, Significantly Modified, and Affected Systems

Proprietary data retained. Contact Author

Appendix G – Proprietary Case Studies

Proprietary data retained. Contact Author

Appendix H - Glossary of Acronyms

Acronym	Description
AC	Airworthiness Circular
ARP	Aerospace Recommended Practice
ATA	Air Transport Association
ATL	Actual Transient Level
ED/AD	Environmental Deterioration/Accidental Damage
EDTL	Equipment Transient Design Level
EME	Electromagnetic Effects
ETSL	Equipment Transient Susceptibility Level
EUT	Equipment Under Test
FAA	Federal Aviation Administration
GVI	General Visual Inspection
HIRF	High Intensity Radiated Fields
LRU	Line Replaceable Unit
RF	Radio Frequency
SAE	Society of Automotive Engineers
TCL	Transient Control Level

References

Chapter 2 References

[2.1] Lightning, by M. A. Uman, McGraw Hill, New York, 1969

[2.2] Lightning Protection of Aircraft Second Edition, by Fisher, Perala, and Plumer, Lightning Technologies Inc., 2004

[2.3] "Aircraft Lightning Zoning", Aerospace Recommended Practice ARP5414, SAE International, Warrendale, PA, December 1999.

[2.4] "Deaths and Injuries as a Result of Lightning Strikes to Aircraft", Aviation, Space and Environmental Medicine, Vol. 66, No. 7, July 1995

[2.5] "Lightning and Aircraft (Part 2)", The Airline Pilot, by the Editors - Lockheed Service Digest, November 1964, page 13

[2.6] "Triggered Lightning", Special Issue of IEEE Transactions on Electromagnetic Compatibility entitled "Lightning and Its Interaction with Aircraft" May 1982, by Clifford, D. W. and Kasemir, H. W.

[2.7] US Civil Aeronautics Board File Number 1-0015, February 25, 1965 (replaced by the US National Transport Safety Board in 1967)

[2.8] "Pilot reports and Lightning Effects", Data from the Airlines Lightning Strike Reporting Project, J. Anderson Plumer, Lightning Technologies Inc., Pittsfield Massachusetts, August 2001.

[2.9] Optical Transient Detector developed in-house at NASA's Marshal Space Center in Huntsville Alabama is a combination of sensor components specially designed to detect lightning and now orbits the earth after its launch in April of 1995

[2.10] "UAL Turbojet Experience with Electrical Discharges", Harrison, H.T., UAL Metrology Circular No. 57, January 1967

[2.11] "Lightning Strike Survey Report for the Period of January 1965 through December 1966", Federal Aviation Agency report of the Conference on Fire Safety Measures for Aircraft Fuel Systems, Appendix II, Department of Transportation, Washington DC, December 1967

[2.12] "Aircraft lightning Environment and related Test Waveforms", Aerospace Recommended Practice ARP5412, SAE International, Warrendale, PA, Original November 1999, Revised February 2005

[2.13] "Direct Effects of Lightning", IEEE, Transactions on Electromagnetic Compatibility, Vol. EMC-24, No. 2, May 1982

[2.14] "Endpoints" Scientific American Magazine; December 2001; by Staff Editors; 1 Page(s) commentary by Edward J. Rupke, Lightning Technologies in Pittsfield, Mass

[2.15] RTCA DO-160E, December 9, 2004 prepared by Special Committee, SC-135, 2004 RTCA Inc.

[2.16] MIL-STD 1757A, "Lightning Qualification Test Techniques for Aerospace Vehicles and Hardware", 1983

[2.17] Terri He and Brian Kuhlman, "Investigation Of Test Methods For DO-160 Qualification Tests", IEEE Symposium on EMC, 2003 IEEE Symposium on Electromagnetic Compatibility, Boston, MA August 18-22, 2003 (ISBN 0-7803-7835-0)

[2.18] Professor J. Fielding and G. James Sweers, "Industry Improvements to Lightning/HIRF Protection Maintenance Program Development", International Conference on Lightning and Static Electricity, September 19-23, 2005, Seattle, WA

[2.19] Christopher C R Jones, "The Lightning Indirect effects Clearance Process for Aircraft", EMC Compliance Journal – (published by the EMC compliance Journal at www.compliance-club.com) located at Nutwood UK Limited, Eddystone Court, De Lank Lane, St Breward, Bodmin, Cornwall. PL30 4NQ.
[2.20] G. James Sweers, paper titled "Use of New Methodology for Lightning/HIRF Maintenance Program Development" presented at meeting of ATA Maintenance Programs Industry Group (MPIG) on June 3, 2005, Ft Lauderdale FL, USA
[2.21] FAA Airworthiness Circular AC 20-136, Protection of Aircraft Electrical/Electronic Systems against the Indirect Effects of Lightning, 3/05/90
[2.22] Richard Kolodziejczyk, "Protection and Certification of Aircraft Avionics Systems from Lightning In-Direct Effects", 13th International WROCLAW Symposium and Exhibition on Electromagnetic Compatibility, June 25-28, 1996) EMC Symposium (published by the WROCLAW symposium at www.emc.wroc.pl) located at Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland
[2.23] C.C.R. Jones and Shawn Powell, Joe Gallagher, "Waveform Comparisons Between Qualification Data and Aircraft Measurements", SAE Technical Paper 2001-01-2917, Proceedings from the 2001 Aerospace Congress
[2.24] EMI/HIRF Induced Lightning Qualification Test Report and procedures for Portable Accelerometer Recorder. October 31, 2001 by C.J. Brady (Proprietary)
[2.25] Industry meeting ATA Task Force on lightning/HIRF protection MSG-3 analysis methodology improvements Seattle, WA USA – July 19-21, 2005. Attended by Airbus, Boeing, Bombardier, Gulfstream, Embraer, FAA, Transport Canada and airline participation. Proceedings published by Air Transport Association of America (ATA)
[2.26] FAA Advisory Circular AC 121-22A, "Maintenance Review Board Procedures", 03/07/97 (published by the FAA at www.faa.gov)
[2.27] Society of Automotive Engineers (SAE) Aerospace Recommended Practice (ARP) 5413 titled, "Certification of Aircraft Electrical/Electronic Systems for the Indirect Effect of Lightning", Issued November 1999
[2.28] Society of Automotive Engineers (SAE) Aerospace Recommended Practice (ARP) 5412 titled, "Lightning Environment Waveforms", Issued 1999, Revised 2005
[2.29] Society of Automotive Engineers (SAE) Aerospace Recommended Practice (ARP) 5416 titled, "Aircraft Lightning Test Methods", Issued 2005-03
[2.30] National Transportation Safety Board. 2000. In-flight Breakup Over The Atlantic Ocean, Trans World Airlines Flight 800, Boeing 747-131, N93119, Near East Moriches, New York, July 17, 1996. Aircraft Accident Report NTSB/AAR-00/03. Washington, DC

Chapter 3 References

[3.1] "MSG3 process application", by Jean-Patrick Moreau, Alexandre de Vulpian, and Fabrice Tristant - Dassault Aviation, 78 Quai Marcel Dassault, 92552 St Cloud, France, Paper presented at International Conference on Lightning and Static Energy (ICOLSE) August 28-31, 2007 Paris, France
[3.2] JAA Administrative & Guidance Material (AGM)
[3.3] Federal Aviation Administration guidance, FAA Advisory Circular 121-22A: Maintenance Review Board Procedures, dated 3/7/97
[3.4] "Industry Improvements to Lightning/HIRF Protection Maintenance Program development Methodology", G.J. Sweers and J.P. Fielding presented at International Conference on Lightning and Static Energy (ICOLSE) conference, June 2005.

[3.5] ATA MSG-3, “Operator/Manufacturer Scheduled Maintenance Development”, document containing MSG-3 analysis guidance, Revision 2007.1 Published by Air Transport Association of America, Inc.
[3.6] “Use of Qualification Testing in Determining Aircraft Continued Airworthiness of Lightning /HIRF Protection”, technical paper presented to 6th AIAA Aviation Technology Integration and Ops (ATIO), September 25th 2006, G. James Sweers, Professor J.P. Fielding, Robert Steinle
[3.7] “Aircraft maintenance costs: A Review of the Third-Party Maintenance Market”, by Jason Lawley, MSc Thesis academic year 2003-2004 Cranfield University School of Engineering – Air Transport Group

Chapter 5 References

[5.1] FAA Advisory Circular AC20-53A, "Protection of Airplane Fuel Systems against the Fuel Vapor Ignition due to Lightning", dated 4-12-85.
[5.2] FAA Advisory Circular AC20-136, "Protection of Aircraft Electrical/Electronic systems against the Indirect Effects of Lightning", dated 3-5-90.
[5.3] RTCA/DO-16OC, "Environmental Conditions and Test Procedures for Airborne Equipment"
[5.4] Paper titled “Environmental Conditions and Test Procedures for Airborne Equipment” written by Mel Clark of Microsemi Corporation, Scottsdale AZ published in MicroNotes technical publication as MicroNote™ 126, July 2004.
[5.5] Society of Automotive Engineers SAE Technical Paper Series 2001-01-2933 Titled “Precipitation-Static (P-Static) Overview of Composite Aircraft” by Jerry W. Thornell, The Boeing Company, Phantom Works
[5.6] “Introduction to Aircraft Design” by J.P Fielding Cambridge University Press 1999 ISBN 0 521 44319 9 (hc)
[5.7] “Aircraft Design: A Conceptual Approach” by D. P. Raymer ISBN 1-56347-829-3
[5.8] Bower, Joseph L. & Christensen, Clayton M. (1995). "Disruptive Technologies: Catching the Wave" Harvard Business Review, January-February 1995
[5.9] U.S Patent Filing for application filed on: 7/9/2008. Invention Disclosure No. 07-0971, Titled: ”Methods and Systems for Evaluating a Design of an Aircraft”, USPTO application number 12/170,317, G.Sweers/The Boeing Company
[5.10] OEM internal document number (Doc number retained), “Aircraft C Series Fuel Tank System Safety Assessment for FAA Special Federal Aviation Regulation No. 88 (SFAR 88)”, Vol. 3, Sec. 9.1.1
[5.11] Fisher, F.A., and J.A. Plumer, Aircraft Lightning Protection Handbook, U.S. Department of Transportation Federal Aviation Administration, September 1989
[5.12] David M. Cook (2003). The Theory of the Electromagnetic Field. Courier Dover. p. 157. ISBN 9780486425672
[5.13] Serway, Raymond A., Robert J. Beichner, and John W. Jewett, Jr., Physics For Scientists and Engineers with Modern Physics, Fort Worth, 2000
[5.14] Final Report performed by National Institute for Aviation Research Wichita State University 1845 Fairmount Avenue Wichita, KS 67260-0093 under sponsorship of U.S. Department of Transportation Federal Aviation Administration Office of Aviation Research Washington, DC 20591 Titled: “GENERAL AVIATION LIGHTNING STRIKE REPORT AND PROTECTION LEVEL STUDY” by J.B. O’Loughlin and S.R. Skinner report number DOT/FAA/AR-04/13, August 2004.

[5.15] SFAR No. 88--Fuel Tank System Fault Tolerance Evaluation Requirements, Docket No. FAA-1999-6411, Effective Date 12/09/2002
[5.16] "Metro III – Lightning can be hazardous", Flugunfall – Information Bulletin V98 Braunschweig, November 1991, Accident Investigation Bureau at Luftfahrt-Bundesamt (LBA) LBA was established as the supreme Federal Authority to fulfill tasks in the field of civil aviation in Germany.
[5.17] "Report on the Aircraft Accident at Bodo Airport on 4 December 2003 involving Dornier DO 228-202 LN-HTA, operated by Kato Airlines AS", SL Report 2007/23, Accident Investigation Board Norway (AIBN)
[5.18] "Use of Qualification Testing in Determining Aircraft Continued Airworthiness of Lightning /HIRF Protection", technical paper presented to 6th AIAA Aviation Technology Integration and Ops (ATIO), September 25th 2006, G. James Sweers, Professor J.P. Fielding, Robert Steinle
[5.19] Christopher C R Jones, "The Lightning Indirect effects Clearance Process for Aircraft", EMC Compliance Journal – (published by the EMC compliance Journal at www.compliance-club.com) located at Nutwood UK Limited, Eddystone Court, De Lank Lane, St Breward, Bodmin, Cornwall. PL30 4NQ.
[5.20] Society of Automotive Engineers (SAE) Aerospace Recommended Practice (ARP) 5413 titled, "Certification of Aircraft Electrical/Electronic Systems for the Indirect Effect of Lightning", Issued November 1999
[5.21] OEM internal document (Aircraft Certification) number (Document number retained), "New and Significant Modified Systems, Equipment and Structures on the (aircraft type retained)", Revision L, February 23, 2007.
[5.22] Society of Automotive Engineers (SAE) Aerospace Recommended Practice (ARP) 4761, "Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment", Issued 01 December 1996.
[5.23] U.S. Federal Aviation Regulation (FAR) 25.1529, "Instructions for Continued Airworthiness"
[5.24] FAA Memorandum titled, "Policy Statement on Guidance for Determination of System, Hardware, and Software Development Assurance Levels on Transport Category Airplanes", dated January 15, 2004
[5.25] FAA Advisory Circular AC25-19, "Certification Maintenance Requirements" dated 11/28/94.
[5.26] Society of Automotive Engineers (SAE) Aerospace Recommended Practice ARP4754, "Certification Considerations for Highly-Integrated or Complex Aircraft Systems", issued 1996-11
[5.27] Military Standard Document number MIL-B-5087, "Bonding, Electrical, and Lightning Protection, for Aerospace Systems", original publication 1949.
[5.28] Society of Automotive Engineers (SAE) Aerospace Recommended Practice ARP5412, Revision A, "Aircraft Lightning Environment and Related Test Waveforms," February, 2005
[5.29] OEM internal document (document number retained) specification titled, "Bonding and Grounding Specification". The specification contains the engineering requirements for the installation, testing and inspection of electrical bonds.
[5.30] Military Standard Document number MIL-STD-464, "Electromagnetic Environmental Effects Requirements for Systems", issued March 18, 1997.

[5.31] Military Standard Document number MIL-STD-889B, “Dissimilar Metals”, issued July 7, 1976
[5.32] OEM internal document (Aircraft Certification) number (Document number retained), “(Aircraft type retained) Lightning Indirect and Direct Effects Certification Report”, August 20, 1997
[5.33] OEM internal document number (Document number retained), “Electromagnetic Interference Control Requirements”, July 24, 2002
[5.34] OEM internal document number (Document number retained), “HIRF/Lightning Protection Continued Airworthiness Requirements”, March 6, 2007
[5.35] SAE Technical Paper Series 2001-01-2889, “Continued Electromagnetic Protection of Aircraft and Systems”, Michelle Cronkleton and Chuck Beuning, Cessna Aircraft Company
[5.36] US DOT Study Final Report, “Aircraft Wiring Harness Shield Degradation Study”, August 2004 by J.B. O’Loughlin and S.R. Skinner from the National Institute for Aviation Research Wichita State University
[5.37] OEM internal document (Aircraft Certification) number (Document number retained), “(Aircraft type retained) HIRF/Lightning System and Equipment Qualification List”, May 19, 1998
[5.38] ATA MSG 3 “Operator/Manufacturer Scheduled Maintenance Development”, 2007.1, Published by Air Transport Association of America, Inc.
[5.39] Military Standard Document number MIL STD-810B, “ENVIRONMENTAL TEST METHODS (15 JUN 1967)”, This standard establishes uniform environmental test methods for determining the resistance of equipment to the effects of natural and induced environments peculiar to military operations.
[5.40] OEM internal document (Aircraft Certification) number (Document number retained), "(Aircraft type retained) HIRF Certification Plan," Rev. C, dated 6-28-97.
[5.41] OEM Document (Document number retained), "General Technical Requirements for Electrical/Electronic Equipment," Rev. B, dated January 12, 1995.
[5.42] US Federal Aviation Regulation FAR 25.581 titled, “LIGHTNING PROTECTION”, Notice of Proposed Rulemaking. Notice No. 68-18; Issued on 08/16/68. Final Rule. Docket No. 9079; Issued on 04/01/70.
[5.43] US Federal Aviation Regulation FAR 25.954 titled, “FUEL SYSTEM LIGHTNING PROTECTION”, Notice of Proposed Rulemaking. Notice No. 65-43; Issued on 12/28/65. Final Rule. Docket No. 7095; Issued on 08/07/67.
[5.44] US Federal Aviation Regulation FAR 25.981 titled, “FUEL TANK IGNITION SOURCE PREVENTION GUIDELINES”, Notice of Proposed Rulemaking. Notice No. 99-18; Issued on 10/26/99. Final Rule. Docket No. FAA-1999-6411; Issued on 4/19/2001. Final Rule. Docket No. 2005-22997; Issued on 7/9/08
[5.45] US Federal Aviation Regulation FAR 25.863 titled, “FLAMMABLE FLUID FIRE PROTECTION”, Notice of Airworthiness Review Program No. 2; Notice No. 75-10; Issued on 02/27/75. Notice of Airworthiness Review Program No. 3; Notice No. 75-19; Issued on 05/13/75. Notice of Airworthiness Review Program No. 5; Notice No. 75-23; Issued on 05/19/75. Notice of Airworthiness Review Program No. 7; Notice No. 75-26; Issued on 06/09/75. Notice of Airworthiness Review Program No. 8; Notice No. 75-31; Issued on 06/30/75. Final Rule. Docket No. 14324, 14606, 14625, 14685, 14779; Issued on 10/10/78.

[5.46] US Federal Aviation Regulation FAR 25.1203 titled, “IN-FLIGHT MONITORING OF FIRE DETECTION SYSTEMS”, Notice of Proposed Rulemaking. Notice No. 64-28; Issued on 05/14/64. Final Rule. Docket No. 5066; Issued on 11/03/64.
[5.47] Society of Automotive Engineers (SAE) Aerospace Recommended Practice 5414, “Aircraft Lightning Zoning”, Issued December 1999 and Revised February 2005
[5.48] “Recent Data from the Airlines Lightning Strike Reporting Project”, technical paper presented to the AIAA/AHS/ASEE Aircraft Design Systems and Operations Meeting, October 31 – November 2, 1984, J.A. Plumer, Lightning technologies Inc. Pittsfield, MA; and N.O. Rasch and M.S. Glynn, Aircraft and Airport Systems technology Division, Atlantic City Airport, New Jersey USA
[5.49] OEM internal document (Aircraft Certification) number (Document number retained), "(Aircraft type retained) HIRF/Lightning Protection Assurance Plan", dated 08-22-1997
[5.50] OEM internal document (Aircraft Certification) number (Document Number retained), "Aircraft HIRF/Lightning Protection Assurance Validation Test Procedure”, Rev. A, dated 06-28-2006
[5.51] OEM internal document (Aircraft Production Certification) number (Document number retained), " Manufacturing and Engineering Shielding System Integrity Automated Test Equipment Requirements for (aircraft type retained)," Rev. B, dated 10-10-2005
[5.52] OEM internal document (Aircraft Certification) number (Document number retained) MRBR, "(Aircraft type retained) Maintenance Review board Report Document", original dated 07 July 1997
[5.53] “The Aerospace Engineers Handbook of Lightning Protection”, Bruce C. Gabrielson, 1988 by Interference Control Technologies Inc. ISBN 0932263-25-9
[5.54] US Federal Aviation Regulation FAR 25.1316 titled, “System Lightning Protection”, Final Rule Issued 04/20/94
[5.55] US Federal Aviation Advisory Circular AC 40-13-1B, Acceptable Methods, Techniques and Practices – Aircraft Inspection and Repair, Dated 9/8/98. This revision cancels AC 40-13-1A
[5.56] US Federal Aviation Regulation FAR 25.1317 titled, “High Intensity Radiated Fields (HIRF) Protection”, Final Rule Issued 07/30/07

Chapter 6 References

[6.1] SAE Technical Paper IC07/PPR56, 2007, “MSG-3 Process Application”, Jean-Patrick Moreau, Dassault-Aviation, St Cloud France
[6.2] National Aeronautics and Space Administration Technical Memorandum, May 1999, “Lightning Protection Guidelines for Aerospace Vehicles”, by C.C Goodloe, Report Number NASA/TM-1999-209734
[6.3] Institution of Electrical Engineers (IEE) guidance Document on EMC and Functional Safety guidance titled “EMC and Functional Safety in the Aerospace Industry”, by Keith Armstrong, October 20, 2000